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STUD WELDING WITH WELDING CARTRIDGES

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621.791.75

The number of studs welded every day is roughly estimated at over one million, and will certainly increase considerably during the next few years. The importance of an inexpensive and efficient stud welding process, as developed by the writers of the present article, will therefore be evident.

Introduction

Stud welding may be defined as the welding of a rod-shaped object (pin, stud, bolt) to, say, a plate, at right angles, without employing a separate welding electrode. It can be done by means of a resistance weld or by employing the stud itself as a welding electrode, that is, by drawing an arc between the stud and the work.

Steel studs joined to steel surfaces at right angles have a vast number of applications. Some examples are the securing of covers, the assembly of various parts of machines, flange connections, the fixing of facing material to a steel surface (say, wooden planking on a steel deck), or the anchoring of pipe brackets in ships and other steel constructions. The boiler-making industry offers another example, viz. the fixing of studs, in large numbers, to heat exchanger tubes, to increase the overall area of heat transfer. The frontispiece shows studs being fixed inside a steel tank at the "N.V. Werkspoor", Amsterdam, by the recently developed process of stud welding described in the present article.

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Stud welding is much quicker and cheaper than the conventional method of fixing studs, that is, screwing threaded studs into drilled and tapped holes. Moreover, such holes weaken the plates and may cause leaks, objections which apply equally to rivets. Hence it is not surprising that such methods are now being superseded more and more by various stud welding processes.

Resistance welding

In resistance welding, stud and workpiece are pressed together and a strong current is passed through them. The contact resistance between the two results in heat being generated at the point of contact, so that the material is softened. When the material is suitably plastic, the stud and the work are clamped together between the jaws of a press. How much of the cross-sectional area of the stud is actually welded depends upon the current and the pressure employed. The use of a press imposes certain limitations on the size and shape of the workpiece. On the other hand, this method of welding is better than others in that it does not form a collar of weld metal around the base of the stud (*fig. 1*); this is an important advantage for some purposes (e.g. joining flanges).

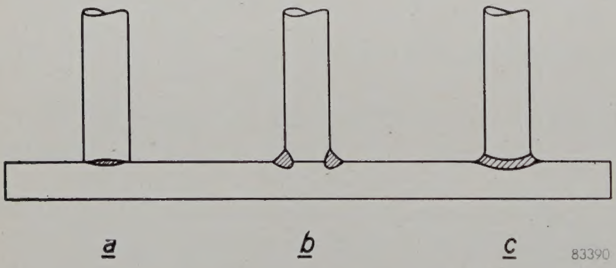

Fig. 1. Difference between the welds produced by the various methods of stud welding.
a) Resistance weld.
b) Arc weld produced with separate welding electrode.
c) Weld produced by drawing an arc direct between stud and plate.

The conventional method of stud welding

Studs can be welded, of course, with an ordinary welding electrode. Although this method generally produces a better joint, and is less limited in scope (e.g. as regards the size of the workpiece) than resistance welding, it requires much time and skill and is therefore rather expensive. In view of this fact, another method, that of drawing an arc direct between the stud and the work, was much used in the ship-building and boiler-making industries during the second world war. Usually, the stud is pressed against the work by a mechanism in the holder (or gun), the current is switched on, and a mechanism at once retracts the stud a fraction of an inch to draw the arc. After a pre-determined interval, in which a suitable amount of molten steel accumulates on the surface of the work and on the end of the stud, a separate unit connected to the gun switches the current off and releases a spring in the gun to press the stud into the molten steel.

For a $\frac{1}{2}$-inch stud, the welding time is of the order of $\frac{1}{2}$ second and the welding current 500-1000 A. Frequently, and invariably in the case of vertical and overhead welding, a porcelain ring ("ferrule") is fitted round the base of the stud to minimise loss or spattering of the molten metal. When the stud is welded, this ring is broken off.

Although quite practicable, this method of stud welding has certain serious disadvantages, largely owing to the fact that the stud, also employed as the welding electrode, is bare; D.C. has therefore to be used, and, since the currents are very heavy, an expensive rectifier is required.

Bare electrodes cannot be welded with alternating current of normal voltages (approx. 80 V), since the arc would then be unstable and liable to extinguish prematurely. Moreover, without special precautions, electrodes not enclosed in a slag-forming coating produce welds of inferior quality. The precautions referred to consist in employing studs made of a special type of steel, and, in some cases, applying deoxidizing agents to the ends of them. It follows that, at least for many purposes, it is necessary to employ studs specially made to suit the particular welding conditions. Also, the equipment required to move the stud in the above-mentioned manner and control the current is rather complex.

It will be evident, then, that the search for a simpler stud welding process is well worth while. The principles and application of a new method evolved as a result of this investigation will now be explained. Some measurements carried out to analyze the new process, and a number of tests on welds produced by it, will then be described. To conclude this article, one or two important practical details will be mentioned.

Principles of the new method

In 1945, the Philips Laboratories at Eindhoven developed what is known as the contact arc-welding process [1]). It involves the use of welding electrodes whose coating is very thick, and is rendered semi-conductive by including in it an appreciable part of the weld metal as a powder. Such welding electrodes ignite and re-ignite very readily; moreover, they are suitable for touch-welding. The new method of stud welding is based on the same principles as contact welding [2]).

Let us now consider what happens when a partly used contact welding electrode, that is, one whose tip contains a deep "cup" formed during welding (*fig. 2*), is applied to a workpiece and the voltage is switched on. The current then flowing through the cup to the workpiece builds up very rapidly, owing to breakdown effects between the individual grains of iron powder in the material forming the cup: the grains fuse together and so produce a rapid drop in resistance. In a very short time, then, the temperature at the point of contact rises enough to strike an arc. Once formed, the cup remains intact throughout the time the electrode is fused, keeping the core wire a certain distance from the work and thus preventing the two from "freezing" together.

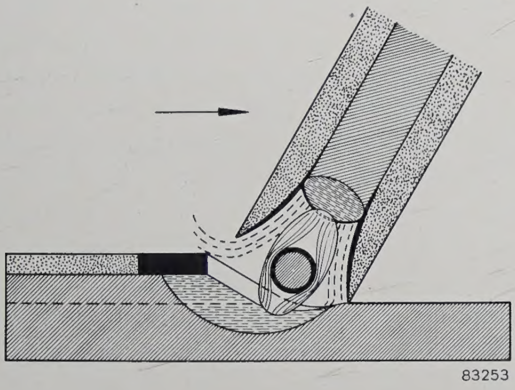

Fig. 2. A deep "cup", formed at the tip of a contact welding electrode during the deposition of metal, prevents the electrode from "freezing" to the work.

Now, if the entire coating of a contact welding electrode, other than a small portion at the tip, be stripped off, and if this electrode is then pressed against the workpiece at right angles (*fig. 3*), the arc produced when the current is switched on will be quite normal at first; however when the remaining portion of the coating is almost consumed, the core wire suddenly breaks through the cup and freezes to the weld metal. This is precisely what is required in stud welding. The fusion time of the electrode is governed by the dimensions and composition of the coating, as well as by the welding current.

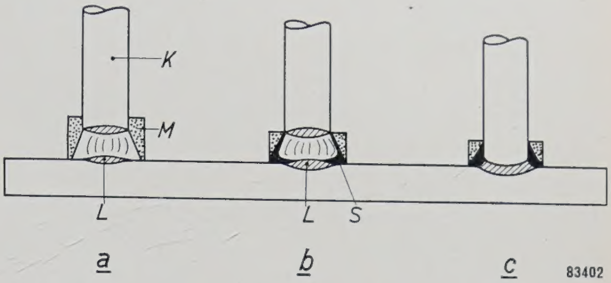

Fig. 3. The different stages in stud welding with a partially stripped contact welding electrode having a "cupped" tip. *M* portion of coating left on the rod, *K* core wire, *L* molten pool of metal, *S* slag.
a) Immediately after the striking of the arc.
b) Just before the electrode drops through the cup. The coating and the core wire have partly melted. A pool of molten metal and a certain amount of slag have been formed.
c) After the electrode has dropped through the cup. The weld metal is covered with slag and the remnant of the cup around the weld helps to shape it.

The basic idea of the new method of stud welding is to make the "coating" separately in short sections, cup-shaped and similar in composition to the coating of the contact electrodes. Fitted to the end of a stud, such a section ("welding cartridge") would enable it to be welded in the same way as the stripped contact electrode described above. These ideas, after many experiments, have led to the simple method now to be described.

The new method of stud welding

The shape of the welding cartridge

A diagram showing the welding cartridge, attached to a stud *A*, as placed on the work to which the stud is to be welded, is seen in *fig. 4*. The cartridge is in two parts, viz. an igniter element, *B*, made of

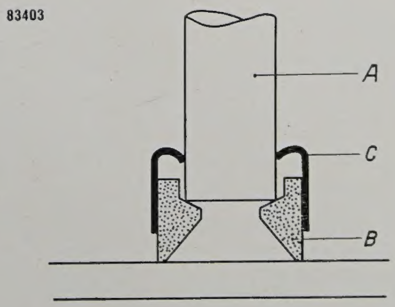

Fig. 4. The welding cartridge, comprising a semi-conductive igniter element *B* and a cardboard collar *C* to hold it on the stud to be welded *A*. During welding, the ridge of the igniter element supporting the stud melts, thus enabling the stud to be pressed into the pool of molten metal.

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[1] P. C. van der Willigen, Philips tech. Rev. **8**, 161-166, and 304-308, 1946; Sheet Metal Ind. **26**, 155, 1949; Schweissen und Schneiden **2**, 270, 1950.

[2] The idea of basing a simple stud welding process on the principles of contact arc-welding came from Dr. H. Bienfait of the Philips Laboratories at Eindhoven.

semi-conductive material, and a cardboard collar C, fitted round the igniter. The igniter has a cup-shaped cavity similar to that acquired by a contact welding electrode, and an inside ridge to support the stud to be welded. One or two studs ($\frac{1}{2}$-inch), together with the associated welding cartridges, will be seen in *fig. 5*. The welding process is very much the same as that of the stripped contact electrode already described. The heat generated by the arc melts the igniter from the inside; when the supporting ridge has melted away, the stud (which is under a certain pressure) shoots into the molten weld metal, the arc is shorted and the stud "freezes" to the work. Whilst the inside of the igniter is melting, its outside remains intact, thus keeping the arc length more or less constant until the stud breaks through the cup.

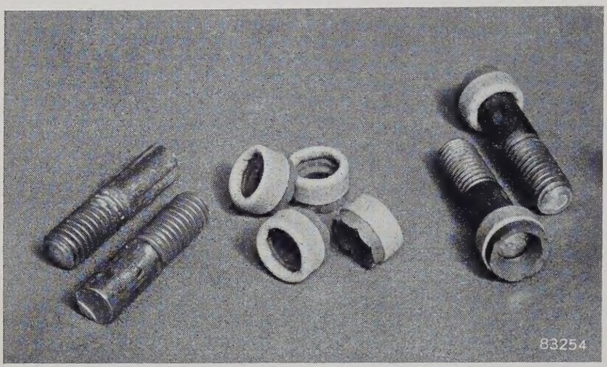

Fig. 5. Threaded studs ($^1/_2$-inch) and the corresponding welding cartridges. Two studs with cartridges fitted are shown on the right of the picture.

The cardboard collar serves two purposes. Firstly, it prevents the rather brittle semi-conductive material of the igniter from disintegrating too soon during the welding process and thus shortening the welding time unduly. Secondly, it holds the welding cartridge on the stud. To enable it to do so, the top edge is curled inwards to fit fairly tightly round the stud. The cardboard is stiff enough to prevent the cartridge from slipping off during handling of the stud.

The use of a cardboard collar is possible by virtue of the fact that the heat generated during the burning of the arc (about 0.5 sec.) does not reach the outside of the igniter until the stud is welded. The cardboard, having served its purpose, then catches fire.

The composition of the welding cartridge

The first experiments were carried out with welding cartridges similar in composition to the coating of a contact electrode. However, it was found that very much stricter requirements as regards freedom from gas and non-sensitivity to moisture must be imposed on the igniter than on the coating of welding electrodes, owing to the fact that no after-heating occurs as is necessarily the case in normal arc welding; the weld metal therefore sets very quickly. Consequently, the probability that any gas occluded in the metal will be able to escape is very much smaller than in ordinary arc welding [3]). The requirement that the igniters be free from gas necessitates heating them during manufacture to a temperature higher than normal for welding electrodes (baking). This must be done in a neutral or reducing atmosphere, to avoid oxidation of the metal powders in the material.

Experiments with different coating-constituents have shown that a low melting point should be avoided. This is not surprising, in view of the fact that the stud is released as soon as the supporting ridge in the igniter melts. If the igniter has a very much lower melting point than the stud, the latter will be released before the end of it is fully molten, and therefore pressed into the welding-pool prematurely.

However, it was found that an igniter composed partly of titanium dioxide (TiO_2) and partly of binding agents, deoxidising metals, and so on, meets all the requirements imposed by this method of welding. The desired conductivity is not obtained by including a certain amount of iron powder, as in contact electrodes. Instead, since the igniter must be baked in a neutral or reducing atmosphere, we take advantage of a well-known characteristic of TiO_2, that is, that in a reducing atmosphere it loses part of its oxygen content and in the process becomes somewhat conductive (semi-conductive). Since the conductivity thus imparted to TiO_2 depends upon the degree of reduction attained under the particular baking conditions, it can be regulated accurately within certain limits. The actual conductivity of the igniter is very critical; if it is too low, the arc will not strike, and if it is too high, too much of the welding current passes through the igniter, causing it to melt prematurely.

The welding gun

In principle, welding with the cartridges described here can be carried out by clamping the stud in a holder (very similar to the type employed in ordinary welding) and pressing it against the work, the welding current then being supplied through the holder. In practice, however, this method has serious objections:

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[3]) See J. D. Fast, Causes of porosity in welds, Philips tech. Rev. **11**, 101-110, 1949/50.

1) It is impossible to place the studs really squarely on the work by hand.

2) When a number of studs of equal length are to be welded, it is very difficult to get them all at exactly the same height, since some of the studs are pressed deeper into the molten pool than others.

3) In the welding of studs the current cannot be switched on and off simply by moving the holder onto or off the work as in normal hand welding.

To avoid these difficulties, it was necessary to design a special holder, or welding gun. The principle of this device is shown in *fig. 6* and its operation explained in the caption.

The stud welding procedure is as follows. The studs to be welded are inserted in the welding gun, which is then adjusted to suit the particular stud length. When a number of studs of the same length (tolerance, say, ±0.2 mm) are to be welded, only this first adjustment is, of course, necessary. Next, a welding cartridge is fitted on the stud, the gun is applied to the appropriate spot on the workpiece and pressed firmly against it. The current is then switched on by means of a switch built into the pistol grip. When the arc (operating period roughly 0.5 sec.) is extinguished and the weld completed, the switch is released, cutting off the short-circuit current. The welding gun is then retracted from the work and the fragments of the welding cartridge are removed from the stud. The interval between switching on and switching off is roughly 2 sec. *Fig. 7* shows the welding gun,

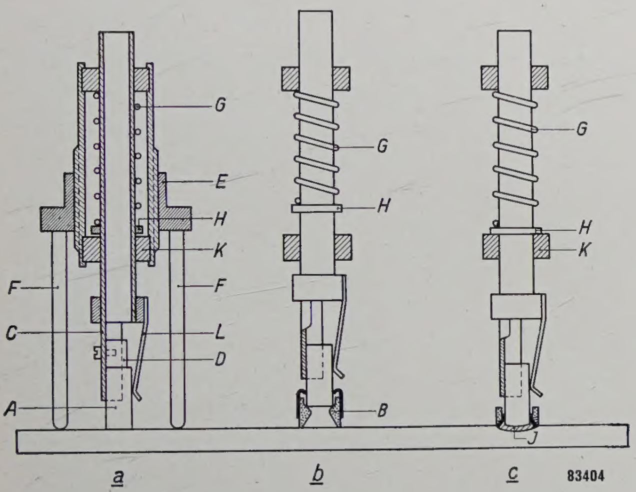

Fig. 6. Diagram to demonstrate the operation of the welding gun.

a) The stud A is clamped in a stud holder C by a flat spring L and rests against a stop D, adjustable to different stud-lengths (coarse adjustment). A threaded ring E (fine adjustment) enables the bottom face of the stud to be adjusted to a level about 0.5 mm beyond the plane passing through the ends of the supports F. This can be done with the aid of a simple jig, e.g. a flat plate about 0.5 mm thick with a hole, somewhat larger in diameter than the stud, at the centre; this plate is so positioned against the supports that the end of the stud just enters the hole. A spring G presses the stud on to the workpiece.

b) A welding cartridge B is fitted on the stud. As the gun is pressed against the workpiece, collar H is pushed upwards, thus compressing spring G. The current is then switched on and an arc is struck. When the part of the igniter supporting the stud melts, the stud is pressed on to the workpiece by spring G.

c) When once the stud is welded, collar H rests on stop K; this ensures that each stud is pressed equally far into the polten pool of metal. The amount of "excess" weld metal at J depends upon the distance to which the stud originally protudes (0.5 mm).

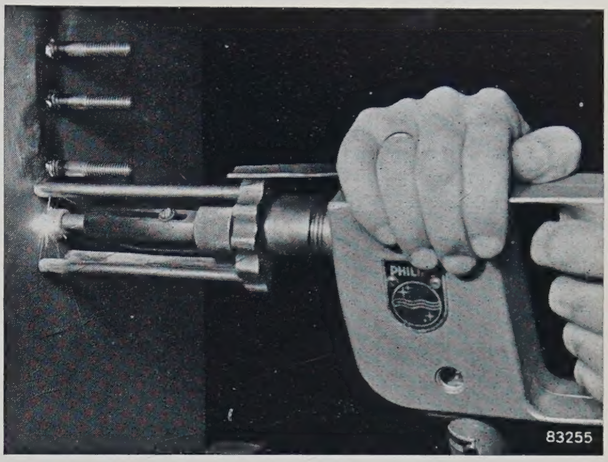

Fig. 7. Welding a $^3/_8$-inch stud to a vertical wall by the new method with a welding cartridge.

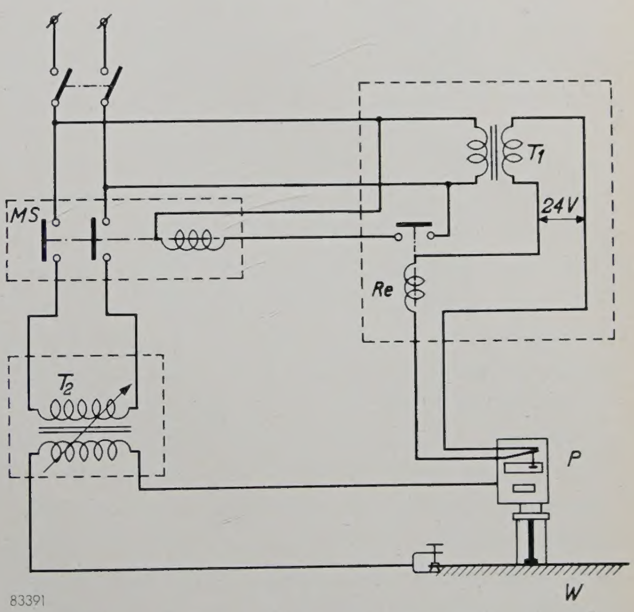

Fig. 8. Circuit of the electrical equipment employed in the new stud welding process with welding cartridges. This process enables alternating current to be used, which means that ordinary welding transformers (open-circuit voltage roughly 75 V) can be employed. A micro-switch built into the grip of the welding gun P operates the coil of a relay Re. Since the energising voltage of this relay is only 24 V (transformer T_1), the micro-switch can be touched without risk, even when defective. The relay operates a magnetic switch MS controlling the welding transformer T_2. W is the workpiece to which the stud is to be welded.

with stud and cartridge fitted, being used to weld a stud to a vertical plate. *Fig. 8* is the circuit diagram.

Comparison of the new technique with the conventional method

Comparing the new method of stud welding with the one usually employed hitherto, we see that the disadvantages associated with the latter are now eliminated. Firstly, the new method incorporates all the advantages of coated, as compared with bare welding electrodes. Amongst other things, the coating serves a metallurgical purpose (that is, not only in producing slag to react with the molten metal and the impurities in it, but also in introducing alloying constituents into the weld), thus enabling studs of ordinary commercial steel to be employed; hence it is no longer necessary to employ studs made of special steels. Another important task of the coating is to reduce the amount of nitrogen absorbed from the atmosphere. Filing tests on welded joints have shown that hardness owing to the formation of nitrides in the weld is very much less noticeable in the new, than in the old process. Moreover, the coating also contains substances which emit electrons readily when heated, thus stabilizing the arc. This arc stabilization enables low-frequency (say, mains-frequency) alternating current, and a relatively low voltage, to be employed. The advantages of A.C. welding (inexpensive welding equipment, less arc "blow") need not be pursued further here.

Secondly the welding cartridge itself strikes the arc and keeps the length of it constant throughout the welding period. Also it automatically leaves a clear path between stud and work at the end of the prescribed arc period. Accordingly, no special means have to be built into the welding gun and the associated equipment to achieve this behavior. The equipment is therefore relatively simple and inexpensive. It will be seen from fig. 8 that apart from a simple mechanism to grip the stud and press it home, the welding gun itself contains only one switch. The associated equipment, apart from the welding transformer T_2, includes only a relay *Re* with a transformer T_1 (both housed in the same box) and a magnetic switch *MS*.

Measurements on the process

To study the welding process stage by stage, the voltage, the current and the distance between stud and work were plotted as functions of time with the aid of a recording instrument. *Fig. 9* shows a diagram recorded by this instrument during the welding of a ½-inch stud to a plate. Note the three distinct stages, which are revealed most clearly by the voltage diagram.

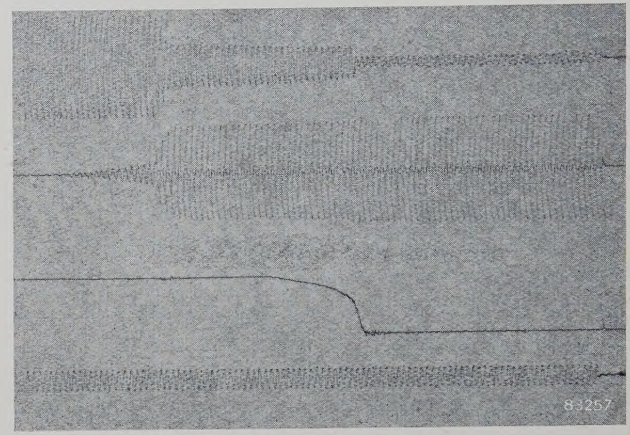

Fig. 9. Diagram recorded during the welding of a ½-inch stud. Starting at the top we have, plotted against time: the voltage, the current, the displacement of the stud, and a constant 50 c/s A.C. voltage which serves as a time scale.

During stage one, the voltage is almost equal to the open-circuit voltage of the welding transformer (about 80 V). The current (ignition current in the conductive igniter) builds up gradually. Stage two begins with the striking of the arc and continues while the arc burns. The voltage drops to the arc voltage (about 40 V) and the current increases to roughly 700 A. The inside of the igniter body begins to soften about 0.4 sec. (20 cycles) after the striking of the arc; the softening is manifested by a gradual sinking of the stud (see third curve in diagram). When the whole of the stud-supporting ridge inside the igniter has melted, the stud is suddenly thrust into the molten pool of metal; this is indicated by the steep slope of the displacement curve in the diagram.

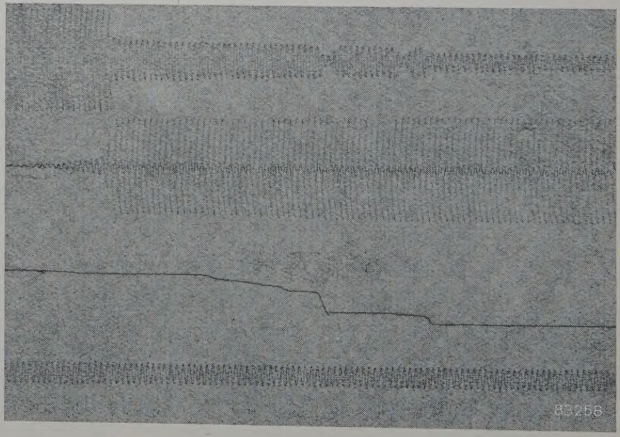

Fig. 10. As fig. 9, but recorded during the welding of a ½-inch stud with a coarse thread on the end to be welded. The stud then drops intermittently, thus producing an inferior weld. Premature melting of the screw thread is a possible cause.

The stud and the plate are thus joined, and the current then increases slightly to the short-circuit value. It can then be switched off, and the gun can be withdrawn. However, it is advisable to wait some tenths of a second after the arc is extinguished before withdrawing the gun, so that the metal has time to solidify.

Diagrams such as that in fig. 9 are very useful for studying the welding process, in that they depict the effects of various variables. For example, *fig. 10* shows the trace obtained during the welding of a $\frac{1}{2}$-inch stud, provided with a rather coarse thread at the end to be welded, under conditions otherwise similar to those of fig. 9. The most interesting feature of fig. 10 is the displacement curve, showing that here the stud drops intermittently instead of smoothly. It is possible that the thread resting on the supporting ridge inside the igniter begins to melt before the ridge itself has melted. Consequently the stud is enabled to drop slightly, causing a short-circuit as indicated by the voltage diagram. After about 0.02 sec. the arc is re-established, only to be extinguished again after a further interval of roughly 0.1 sec; it is again restored, and the stud then drops still lower, producing another short-circuit, and remains where it then is. The total displacement is less than in the preceding diagram, and investigation has shown that, in consequence, the stud is not properly welded to the plate. In practice, the operator can hear from the irregular sound of the arc that the welding is not proceeding satisfactorily.

The requirements imposed on the finish of the stud to ensure a good weld are not stringent. The end face should be round, smooth and free from burr and should be at right angles to the stud. *Fig. 11* shows the equipment employed to record the above diagrams.

Properties of the weld

Since the greater part of the weld metal comes from the stud and the plate, the properties and composition of the weld are governed partly by the composition of these components. However, deoxidizing agents incorporated in the igniter ensure that the weld metal solidifies as "killed" steel [4]) (*fig. 12*).

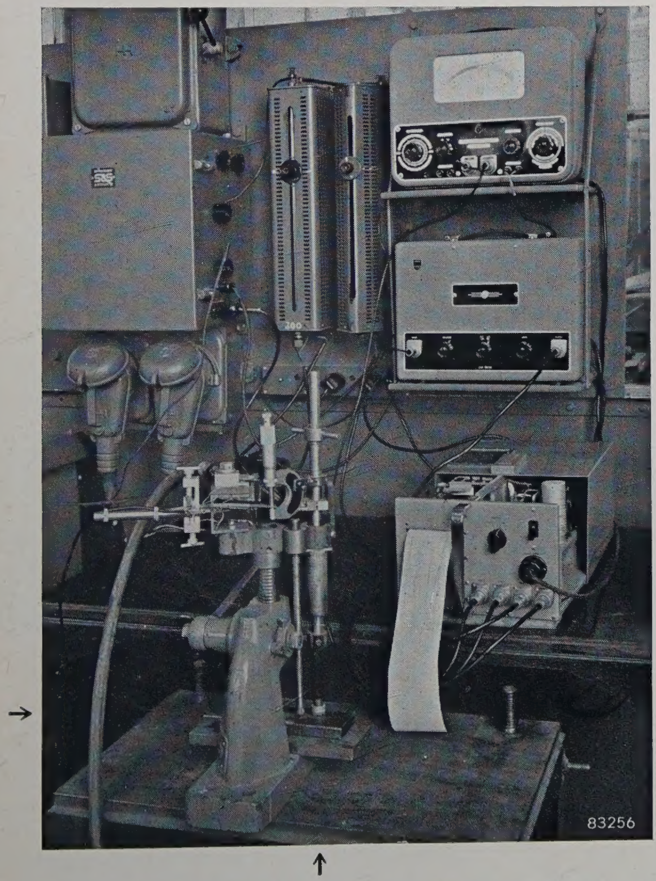

Fig. 11. The equipment employed to record variations in the voltage and the current, and in the distance between the stud and the work, as a function of time during the welding process. The ordinary welding gun was not employed during these measurements. The arrows indicate the position of the welding cartridge.

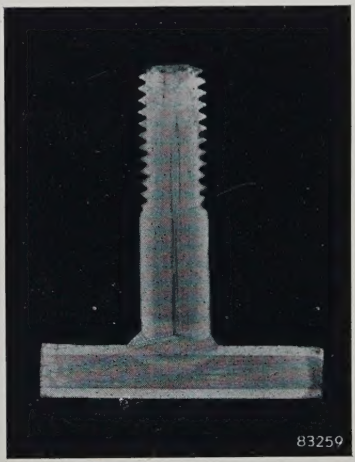

Fig. 12. Cross-section of a $\frac{1}{2}$-inch stud welded to a plate by the cartridge method of stud welding. The slag enclosures revealed by etching show that the stud and the plate are both made of rimmed steel [4]).

The process described here is intended primarily for the welding of studs to unalloyed steel (C-content roughly 0.2%). Depending on the particular requirements to be met by the weld, it is advisable with hardening types of steel to pre-heat the parts to be welded, in order to reduce the cooling rate, and hence limit the hardening.

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[4]) "Killed" steel is steel which generates very little gas when it sets after casting. The gas generated during the setting of rimmed steel causes segregations and porosity.

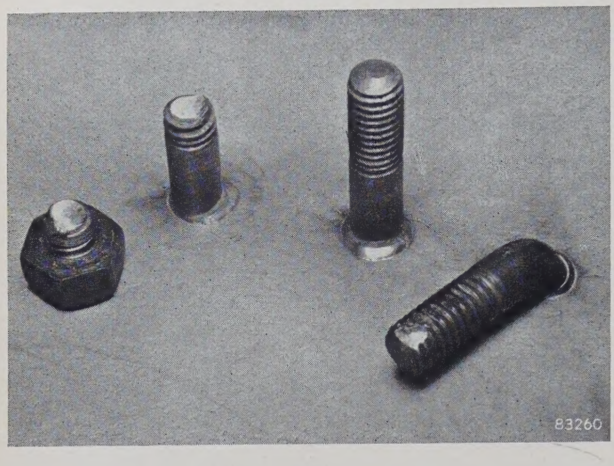
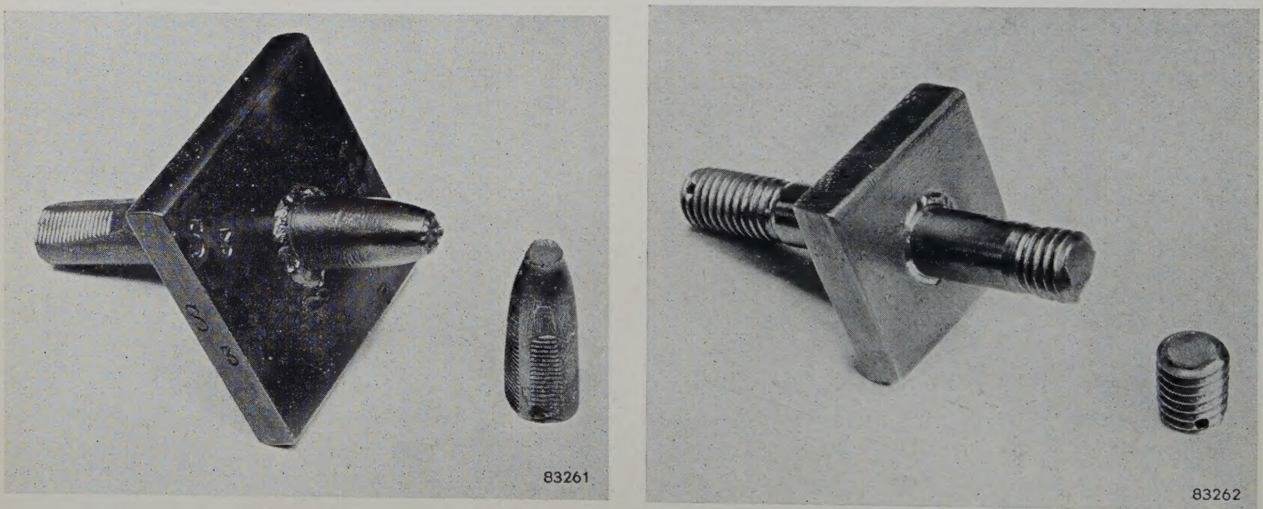


Fig. 13. Simple tests to determine the mechanical strength of the joint between stud and work. Right: a stud bent through 90° by hammering. Left: a stud sheared off by turning a nut against a metal sleeve (not shown in the photograph) fitted round the stud. The part of the stud broken off, with the nut still on it, is seen on the extreme left of the picture.

The simplest method of testing the strength of the weld is to bend the stud, say, by hitting it with a hammer. Experience has shown that a stud of mild steel can be bent in this way to an angle of 90° without cracking (*fig. 13*). With studs or plates of more brittle materials the plastic deformation possible is less.



a *b*

Fig. 14. *a*) Result of a tensile test on two studs welded end to end to oposite sides of a plate.
b) Result of a fatigue test.

Another simple test is to shear off a partly threaded stud by fitting a short metal sleeve round the welded stud, screwing a nut on the stud and tightening it against the sleeve. If the nut is turned far enough, the stud ultimately breaks. With a stud and a plate of mild steel, the weld itself will invariably remain intact and the stud will break where it is threaded, that is, unless the thread itself is sheared off (fig. 13).

Studs without thread can also be subjected to tensile tests by welding two of them end to end to opposite sides of a plate and testing this assembly on a tensile machine. As in the other test, the weld itself normally remains intact and fracture occurs in another part of the assembly (*fig. 14a*).

In a similar way, fatigue tests can be carried out. A series of test pieces, pre-stressed under a tension of 0.25 kg/mm^2 (0.16 tons/in^2), were subjected to alternating stresses of amplitude varying, as between the different tests, from 10 to 20 kg/mm^2 $6\frac{1}{2}$-13 tons/in^2); for practical reasons, the studs used were threaded. These test pieces also fractured in the thread, that is, clear of the weld (fig. 14*b*). The fatigue limit of mild steel studs was found to lie in the region of 15 kg/mm^2 (10 tons/in^2).

Some practical details

Welding cartridges are now made to fit four stud diameters viz. $^{1}/_{2}''$, $^{3}/_{8}''$, $^{5}/_{16}''$ and $^{1}/_{4}''$. The tolerance on the $^{1}/_{2}''$ studs is ± 0.3 mm and that on the others ± 0.2 mm; if the stud is too thin it will drop through the cartridge too soon, thus shortening the welding time unduly, and if it is too thick the welding time will be too long.

With an ordinary welding transformer, the current settings required for the four stud-diameters specified above are 750, 500, 450 and 325 A, respectively. These values apply to welding on relatively thick plates. For thin plates (thinner than about half the stud diameter), the above values should be reduced.

The open-circuit voltage of the welding transformer should be at least 70 V. As we have already remarked in connection with hardening effects, the requirements imposed on the steel to be welded and the material of the stud are not very stringent. Excessive slag enclosures should be avoided, since they may make the weld unduly porous. However, the sulphur content, for example, need not be particularly small, and, provided that the weld is not required to be above average toughness, sulphur alloyed free-cutting steel can also be welded by this technique.

Summary. A new technique for welding studs perpendicularly to a workpiece is described. It involves fitting a welding cartridge on the end of the stud to be welded. This cartridge is made of semi-conductive material; its special functions are: to strike the arc, fix the distance between stud and workpiece and regulate the welding time. The cartridge also fulfils the metallurgical and other functions of the coating of an ordinary welding electrode. By virtue of the metallurgical effect of the cartridge on the weld, it is possible to employ studs of ordinary commercial grade steel. The stabilizing effect of the cartridge on the arc enables alternating current to be employed. The welding gun to position the studs correctly on the work incorporates only simple devices to hold the stud and press it against the work, and a switch to turn the current on and off. A relay and transformer, together with a magnetic switch to control the welding transformer, are all the auxiliary equipment required.

AN X-RAY TUBE FOR MICRORADIOGRAPHY

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For some decades various investigators have been working on the problem of making X-ray photographs of very thin objects, such as insects, sections of animal and plant tissue, metal foils, paper, etc. In view of the small X-ray absorption in such thin objects, very soft X-rays must be used in order to get sufficient contrast; the X-rays must therefore be generated by a rather low voltage X-ray tube (3—10 kV). However, the softness of the X-rays means that very thin tube windows are then necessary e.g. thin aluminium foil. Owing to the difficulty of making such windows vacuum-tight, it has hitherto been necessary to work with a continuously-evacuated tube [1][2].

Following up earlier work [3][4], it has proved possible to make a vacuum-tight beryllium window only 50 μ thick. This is sufficiently transparent to X-rays in the range between 1.5—5 kV (2—15 Å). This window has been used in a small 5 kV sealed-off X-ray tube, a cross-section of which is shown in *fig. 1* and a photograph in *fig. 2*. The tube is incorporated in a small portable apparatus, the CMR 5, which includes the H.T. generator, controls and the camera.

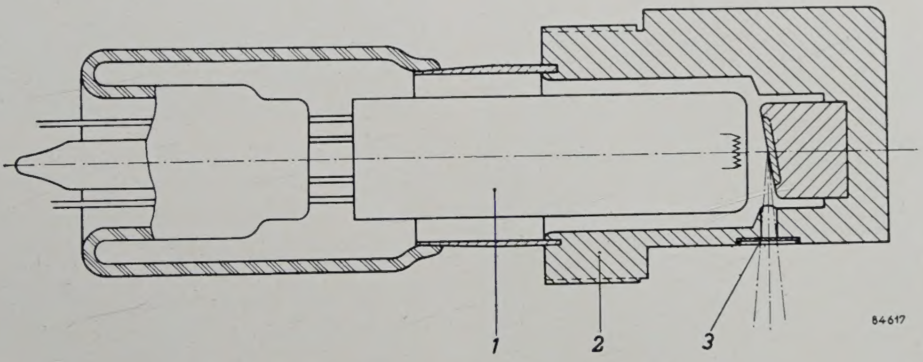

Fig. 1. Cross-section of the 5 kV X-ray tube used in the CMR 5 apparatus. *1* cathode with tungsten filament; *2* anode with tungsten target; *3* beryllium window, 50 μ thick. Length of tube approximately 8 cm.

The sample (mounted on a formvar film across a ring) is placed in contact with the photographic emulsion in the camera: whence the term *Contact Microradiography* (CMR), which has been coined

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[1] P. Lamargue, L'historadiographie, Presse Méd. 478 (1936).

[2] A. Engström, Quantitative micro- and histo-chemical elementary analyses by Roentgen absorption spectrography. Acta Radiol. Suppl. 63 (1946).

[3] B. Combée en P. J. M. Botden, Special X-ray tubes, Philips tech. Rev. **13**, 71-80, 1951/52.

[4] P. J. M. Botden, B. Combée en J. Houtman, An experimental X-ray apparatus with a midget X-ray tube, Philips tech. Rev. **14**, 165-174, 1952/53.

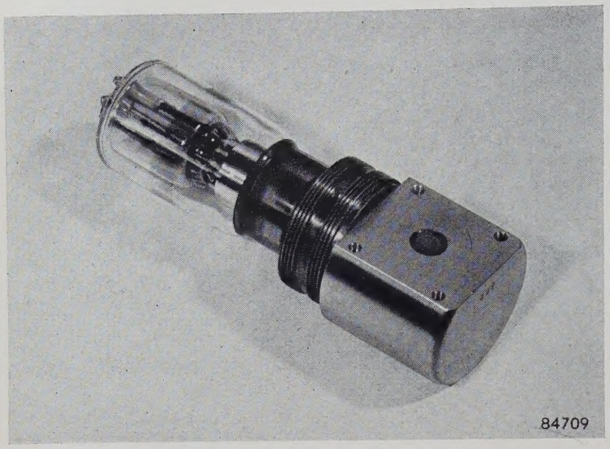

Fig. 2. Photograph of the 5 kV X-ray tube.

for this technique. The full-size radiograph thus obtained is afterwards enlarged optically some hundred times in a light microscope.

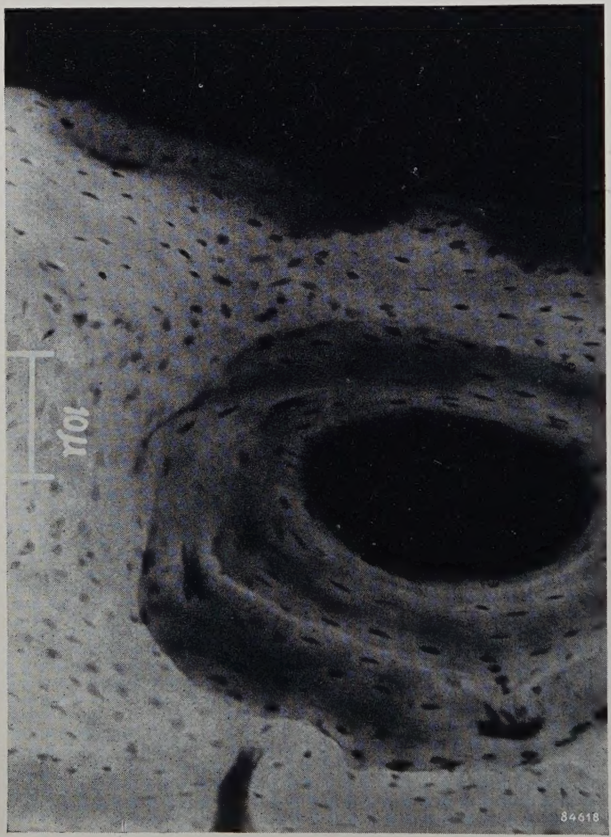

Fig. 3. Bone tissue. To make such a photograph it is unnecessary to de-calcify the bone as in light microscopy; hence it is possible to obtain information on the distribution of mineral salts in the bone (5 kV, 3 mA. Exposure 25 min.)

The resolution achieved with this apparatus is between 0.5 and 1 μ. It is true that this is not quite so good as that obtained with optical microscopes, but because of the much better transparency of materials to X-rays, it is possible to examine many objects which are outside the scope of optical methods.

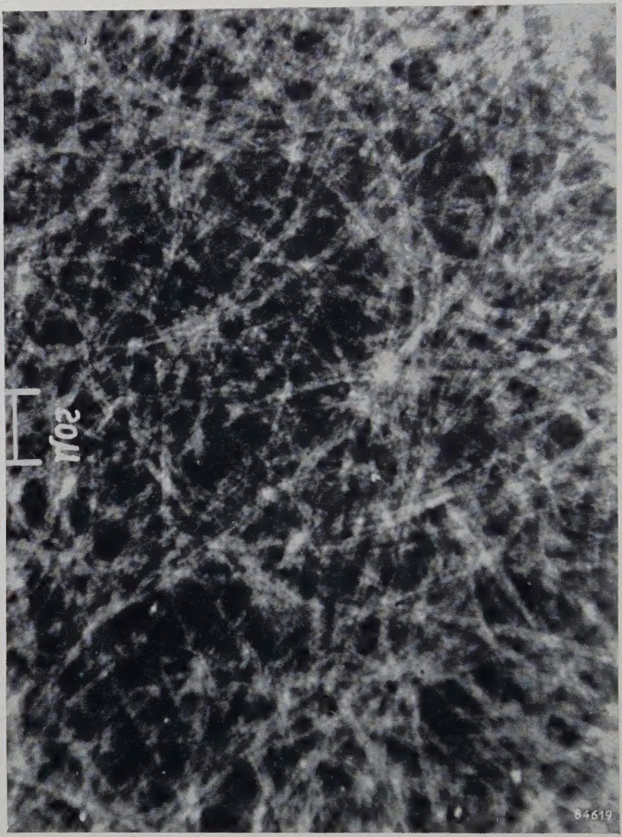

Fig. 4. Paper. The internal texture of the paper is rendered visible by the penetrating power of the X-rays (5 kV, 3 mA. Exposure 10 min.)

The present apparatus, whose price is comparable to that of a good optical microscope, thus brings microradiography within the reach of many workers for whom the construction of an elaborate continuously-evacuated tube was out of the question. X-ray microradiography undoubtedly has a very useful role to play in the region between optical and electron microscopy.

In a later article in this Review these questions will be discussed in some detail.

Meanwhile, the micrographs shown here (figs *3* and *4*) illustrate a few of the possible applications of the technique.

B. COMBÉE

THE EM 75 kV, AN ELECTRON MICROSCOPE OF SIMPLIFIED CONSTRUCTION

by A. C. van DORSTEN and J. B. Le POOLE *).

621.385.833

The electron microscope in its present form is still a complicated and costly instrument. This restricts the number of potential users. Attempts have therefore been made by some designers to simplify the instrument, while retaining as far as possible its valuable features. In this connection, the aims of simpler construction and simplified operation run parallel to the aim of reduced costs.

The magnetic electron microscope described here is basically simpler than most instruments of this type, particularly with regard to the electrical equipment. It does not contain a single amplifying tube. It has, however, apart from other valuable properties, a high resolving power (at least 100 Å).

Introduction

In addition to the EM 100 kV, a magnetic electron microscope with a very high resolving power, Philips have for some time been making a smaller and simpler electron microscope, the EM 75 kV. In developing this instrument it was postulated that a slightly lower resolving power would be acceptable, viz. about 100 A. It was found possible to make the instrument so much cheaper and so much simpler to use that electron-microscopic research may now be expected to be brought within the reach of a much wider circle of scientific research workers than hitherto.

The basic principle of the new apparatus is the use of an objective lens with an extremely short focal length. In this article it will be shown that in this way an electron microscope can be built which, for a given resolving power, sets relatively low requirements as to the maintenance of constant current and voltage, in other words, the aberrations of the image which result from electrical fluctuations are relatively small. By analogy with the optical microscope we may call such aberrations "chromatic" (they arise because the adjustment of the microscope is not correct with respect to the velocity of the electrons, i.e. the wavelength of the electron beam).

It is perhaps of interest to mention in this connection that small chromatic aberration resulting from a short focal length is not a property of electron lenses alone but is equally applicable to the case of optical magnification by means of a glass lens. It is particularly true when one is considering a single uncorrected lens. This was the secret of the microscopes made by Antoni van Leeuwenhoek in the 17th Century: he reduced the faults of the single glass lens to a minimum by making lenses of minute dimensions, with focal lengths as short as possible.

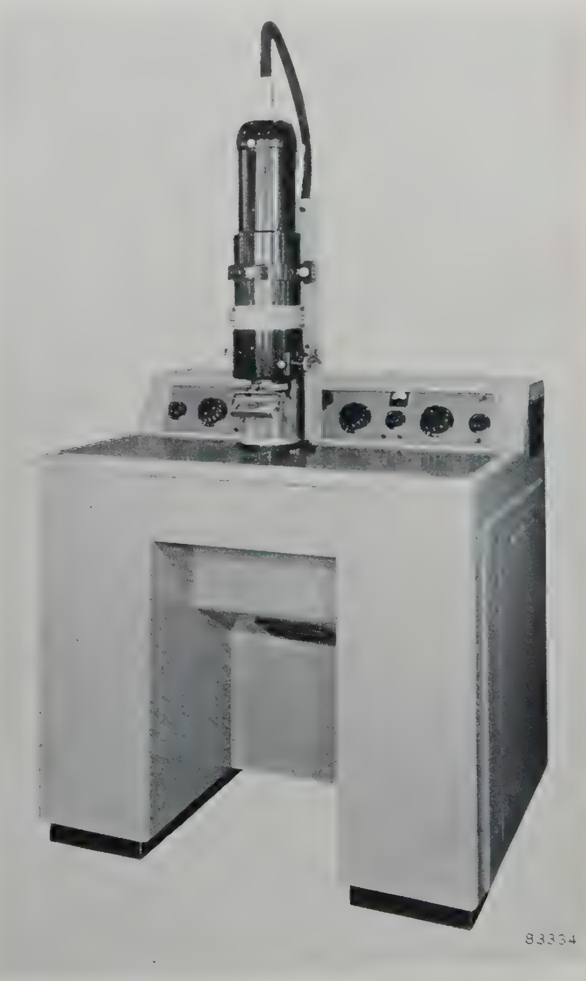

Fig. 1. The small electron microscope EM 75 kV (for 75 kilovolts, type 11981). The electron beam traverses the vertically mounted microscope tube from top to bottom. The desk houses the pump installation and the entire electrical equipment.

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The principles and several practical forms of the magnetic electron microscope have previously been described in this Review ¹)²)³). In this article we shall mainly focus attention on those points in which the new instrument differs from others of this sort. The instrument is shown in *fig. 1*. It is a two-stage microscope, containing three lenses: condenser, objective and projector. We shall now consider in more detail the objective lens, which contains the clue to the new instrument, and the projector.

Focal length and chromatic aberration

A magnetic electron lens consists of a magnetic field, rotationally symmetrical about the axis of the incident electron beam (z-direction, *fig. 2*) and active over a section, generally short, of the electron path. The field is generated by a current-carrying coil of so many ampere-turns (in some types the field is obtained by means of a permanent magnet which is equivalent to a number of ampere-turns). The coil is surrounded by a housing of ferro-magnetic material and in the centre are pole pieces of similar material. In this way the field is concentrated in the small gap between the pole pieces, the electron beam passes through a small circular hole drilled through the centre.

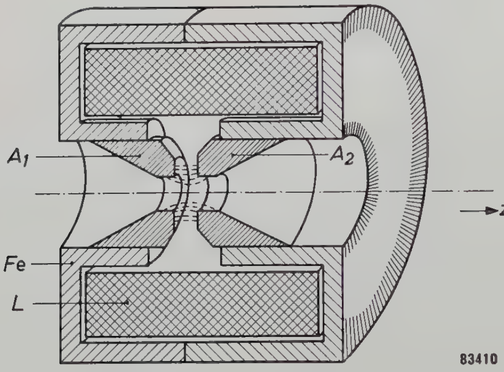

Fig. 2. Magnetic electron lens. L coil, *Fe* iron jacket, A_1, A_2 pole pieces. The electrons move close to the z-axis, which is the axis of rotational symmetry of the magnetic field of the lens.

The focal length f of such a lens for electrons which have been subjected to an accelerating voltage V, is given approximately by the proportion relationship (see e.g. the article quoted in ¹)):

$$\frac{1}{f} \propto \frac{1}{V} \int_{-\infty}^{+\infty} B^2 \, dz \, . \quad (1)$$

B is the induction on the z-axis, along which the integration is carried out. The formula for f actually consists of a series of terms of alternating sign and increasing powers of B^2: in the case of a "thin" lens of moderate power the first term is sufficient.

Small fluctuations ΔV of the voltage V result in changes Δf in the focal length. From (1) it follows that:

$$\Delta f = f \frac{\Delta V}{V} . \quad (2)$$

A similar equation applies to the fluctuations ΔI of the energising current I, which cause fluctuations in the magnetic induction B at all points of the field. If we now consider in particular the objective lens, we can say that the object plane, i.e. the plane which is sharply focused on the fixed fluorescent screen, is not fixed in space but moves to and fro along the axis (while the principal plane of the lens remains more or less in the same place). The object placed in the microscope (specimen) will thus in general be situated at a distance Δv in front of or behind the object plane(*fig. 3*). In this way the "chromatic" blur appears either in visual observation or on the photographic record.

If the magnification is sufficiently large, the object plane nearly coincides with the focal plane; thus

$$\Delta v \approx \Delta f . \quad (3)$$

What was stated above is now qualitatively confirmed. In any case, the chromatic lack of definition will become greater according as the object plane is displaced. Now, from equations (3) and (2), Δv is proportional to f. Therefore, by giving the objective a very short focal length, one can permit relatively large fluctuations of voltage and current for a given chromatic error.

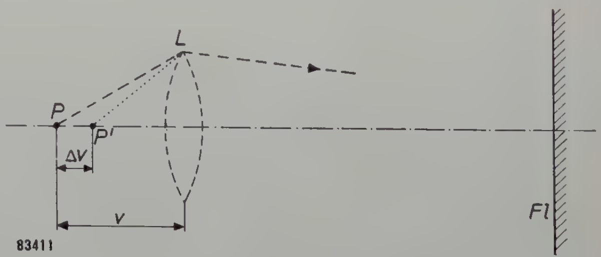

Fig. 3. If the acceleration voltage of the electrons or the excitation current of the objective L vary, the image on the fluorescent screen *Fl* is not that of the object plane P, but is the image of a plane P' displaced by Δv from the object (v is the distance between object and objective lens).

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¹) J. B. Le Poole, A new electron microscope with continuously variable magnification, Philips tech. Rev. **9**, 33-45, 1947/48.

²) A. C. van Dorsten, W. J. Oosterkamp and J. B. Le Poole, An experimental electron microscope for 400 kilovolts, Philips tech. Rev. **9**, 193-201, 1947/48.

³) A. C. van Dorsten, H. Nieuwdorp and A. Verhoeff, The Philips 100 kV electron microscope, Philips tech. Rev. **12**, 33-51, 1950/51.

In order to get a more accurate picture of this relationship, the chromatic blurring can be analysed into two components: a geometrical error, δ_g, and a diffraction error, δ_b. It can be shown that the former is given by:

$$\delta_g = 2a_0 \Delta v\,, \quad . \; . \; . \; . \; . \; . \; . \quad (4)$$

and the latter by:

$$\delta_b = 3\sqrt{\lambda\,\Delta v}\,. \quad . \; . \; . \; . \; . \; . \; . \quad (5)$$

where λ is the wavelength of the electron beam and $2a_0$ the angular aperature of the electron pencil on the object side. This aperture has a different value for each point of the object, depending on the local thickness and density of the specimen. In fact, this is just what makes the image in the electron microscope visible, i.e. gives contrast to the image: the scattered pencils of electrons originating from the various parts of the object have various angular apertures, so that the objective aperture intercepts a different fraction of each, resulting in differences in intensity when they are united in the image plane. For composite (not uniformly thin) objects, such as are usually studied with the electron microscope, "illuminated" by a practically parallel beam of electrons, we can assume a maximum value of $a_0 = 3 \times 10^{-3}$ radians.

The origin of geometrical blur is illustrated in *fig. 4*. The image of the object, due to the change of focal length, does not lie in the plane of the screen, but at a distance Δb from it (b is the image distance, v the object distance). A point in the object is therefore represented on the screen by a small circle of diameter $2r_i \approx 2a_i \Delta b$, $2a_i$ is the (very small) angular aperture of the electron pencil on the image side. If the magnification be M ($= b/v$), a detail in the object of dimensions $2r_i/M$ cannot be distinguished in the image from the blur circle. This is the blur δ_g, related to the object ("resolving power"). By differentiating the geometrical optical lens formula

$$\frac{1}{v} + \frac{1}{b} = \frac{1}{f}$$

it follows that the relationship between Δb and Δv is:

$$\Delta b = M^2 \Delta v.$$

Hence, using the law of Helmholtz-Lagrange $a_i = a_0/M$, one obtains equation 4:

$$\delta_g = \frac{1}{M}\,2r_i = \frac{1}{M}\,2a_i \Delta b = 2a_0 \Delta v.$$

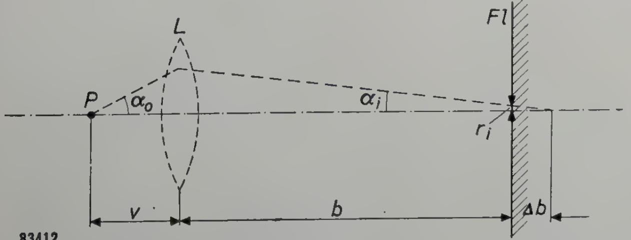

Fig. 4. Illustrating the geometrical blur, δ_g. *P* specimen, *L* electron lens, *Fl* fluorescent screen. (The projector lens can here be neglected.)

The origin of the chromatic diffraction blur can most simply be demonstrated for a "non-transparent" object detail with a sharp edge (*fig. 5*). Behind this detail the scattering is so great that practically no electrons pass through the aperture; beside the object detail the nearly parallel incident rays pass uninterrupted. In the object plane (P' in fig. 3) we have a shadow of the object, and this shadow (which is reproduced truly in the image plane) would be exactly similar to the object at a very small distance Δv, were it not that diffraction effects occur at the edge of the object due to the wave nature of the electron beam. The first order diffraction occurs at a distance r_0 from the edge. We can determine r_0 by applying Huygens' principle which states, for this case: if an object stands in a plane wave causing parts of the wavefront to be absent in some plane beyond the object, then a maximum disturbance will occur at those parts of that plane where rays passing through a point on the edge of the object have a path difference of the order of λ or greater with respect to the undisturbed wave. Thus from fig. 5:

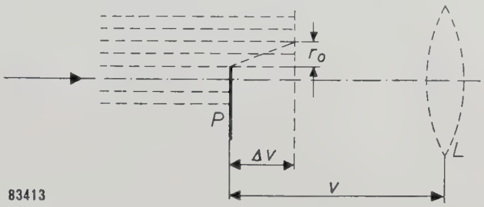

Fig. 5. Illustration of the diffraction blur, δ_b. A parallel electron beam falls on an opaque object *P* from the left. The "shadow" which the object throws on the real object plane at a distance Δv, is sharply reproduced on the fluorescent screen by the lens *L*. The shadow itself is not sharp as a result of diffraction of the electron rays at the edge of the object.

$$\sqrt{r_0^2 + (\Delta v)^2} - \Delta v = \lambda\,,$$

i.e.

$$r_0^2 = 2\lambda\Delta v + \lambda^2\,.$$

Since $\lambda \ll \Delta v$ (otherwise the displacement Δv itself could be neglected), we obtain $r_0 = \sqrt{2\lambda\Delta v}$. The value $2r_0$ gives approximately the width of the Fresnel diffraction fringe associated with the image of a point object, i.e.:

$$\delta_b = 2r_0 \approx 3\sqrt{\lambda\Delta v}\,.$$

Two particles can be resolved separately although their respective diffraction rings partially overlap. The distance, centre to centre between the smallest resolvable particles is, according to Rayleigh's criterion, about $\frac{1}{2}\delta_b$.

From (4) the geometrical blur δ_g is proportional to Δv, and therefore also proportional to the focal length f (see equations 2 and 3); from (5) the diffraction blur δ_b is proportional to $\sqrt{\Delta v}$, i.e. proportional to the root of the focal length. Considered quantitatively with the value of the angular aperture (a_0) already given, and for a wavelength λ corresponding to an acceleration voltage $V = 75$ kV and for an objective of focal length $f = 0.8$ mm (as achieved in the EM 75kV), we find:

a) that the geometrical blur δ_g which must be taken into account in practice, is larger than the diffraction disc δ_b;

b) that for a geometrical blur of 70 Å, the relative variation of the voltage, $\Delta V/V$ may not exceed 1.5×10^{-3}. Of course the voltage is not required to remain permanently constant to this degree, but only long enough after focusing to expose the film. Taking into account other causes of lack of sharpness which are not dependent on voltage fluctuations (spherical aberration, astigmatism of the lens, etc.), the above value of δ_g permits a resolving power better than 100 Å.

Since the focal length of a magnetic lens is dependent on the quantity I^2/V (see equation 1), the requirement of a constant value of the lens current I is twice as strict as for V; in the case under consideration, therefore, the maximum permissible value[4]) of $\Delta I/I$ is 0.75×10^{-3}.

This can be quite easily attained with a simple magnetic stabilizer, consisting of a transformer with saturated core. Electronic stabilization is not necessary for this purpose.

In following this explanation the reader may very well have wondered why we do not use permanent-magnetic lenses to avoid fluctuations. The construction of such lenses with modern permanent magnetic materials is quite feasible [5]), and the problem of keeping the magnetic induction in the lenses constant is then solved. The problem of keeping constant the acceleration voltage, which is technically more difficult and more expensive to solve, remains, however, and is even made more difficult, since it is not possible to make objective lenses with very short focal lengths when using permanent magnets, and the influence of chromatic aberration is therefore relatively large.

Design of an objective of very short focal length

It has been stated above that the objective of the EM 75 kV has a focal length of 0.8 mm. Is it not possible to make this still shorter in order to make the sensitivity to fluctuations still smaller? We shall show that the value given is just about the limit of what can be achieved without undue expense — and that, after all, is the whole point of the thing.

The parameters which are important in this connection are: the choice of the steel for the pole pieces, the length S of the gap between the pole pieces (*fig. 6*), the diameter D of the cylindrical hole in the pole pieces and the excitation of the coil.

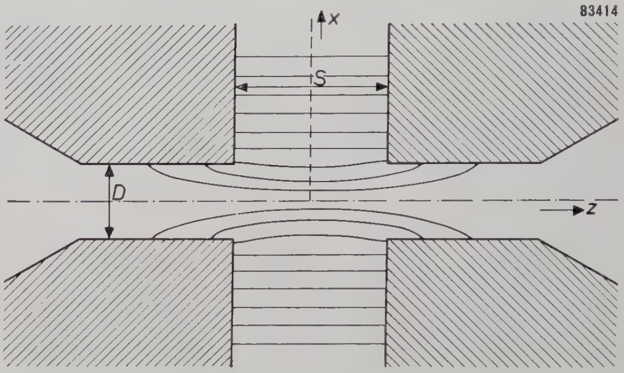

Fig. 6. The configuration of a magnetic lens is characterised by the diameter D of the bore through which the electrons pass (z-direction), and the width S of the gap between the pole pieces.

From equation (1) it may be deduced that a short focal length will be obtained if the induction B is made as great as possible over as long a section as possible of the electron path. For a given lens, B is made greater at all points if the excitation is made stronger. The limit to this is set by the magnetic saturation of the steel. The induction in the pole pieces must remain so far below saturation that the permeability μ is still large, e.g. 1000. At greater induction, for example, so close to saturation that the permeability falls below 50, the types of steel suitable for this use show local magnetic inhomogeneities. Since the induction immediately outside the iron is $1/\mu$ times that in the iron, the field acting on the electrons will also be inhomogeneous and lack the necessary rotational symmetry. Such defects of the field can not only make the image astigmatic but can also result in small deviations of the electron pencil. This latter effect means that the axis of the lens is not straight and that therefore no adequate centring independent of the excitation can be obtained. The consequences of inadequate centring will be discussed later.

The cobalt-iron alloy which we have used has a very high saturation, so that we have been able to raise the excitation to give an induction in the gap between the pole pieces of about 1.8 Wb/m² (18 000 gauss). At the critical points in the magnetic circuit μ is then still greater than 1000.

The problem is thus reduced to the core: the choice of the width of the gap S and the bore D.

Consider now the variation of the magnetic

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[4]) Fluctuations of I as well as of V are caused by variations of the mains voltage. Since an increase in I has the opposite effect on the focal length ot that of an increase in V, one might suppose that fluctuations of I and V would compensate each other partically to such an extent that it would be sufficient to limit relative fluctuations of the mains voltage (to which I and V are proportional) to 1.5×10^{-3}. This reasoning, however is, incorrect since the power supplies for the lens currents and the acceleration voltage involve different time lags, so that correlated fluctuations ΔI and ΔV do not occur simultaneously.

[5]) B. von Borries, Kolloid Z. **114**, 164-167. 1949.
J. H. Reisner and E. G. Dornfeld, J. appl. Phys. **21**, 1131-1139, 1950.

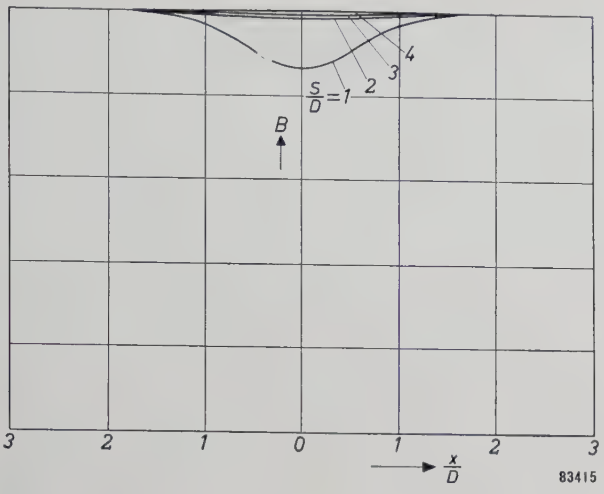

Fig. 7. Variation along the x-axis, see fig. 6, of the magnetic induction B, for lenses with differing values of S/D (the change of field with respect to x/D depends only on this ratio). It has been assumed that each lens is excited so that the maximum induction occurring in the gap reaches a given value (at which no troublesome saturation of the steel of the pole pieces occurs).

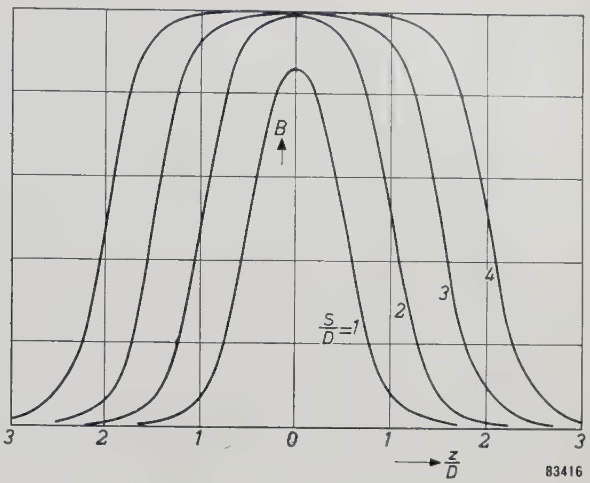

Fig. 8. Variation of the magnetic induction B along the z-axis, for various values of S/D. The induction at $z = 0$ is equal to that at $x = 0$ in fig. 7; the field here is at a saddle point.

field in two mutually perpendicular directions, viz. along the axis of the lens (the z-axis) and perpendicular to it along an arbitrary radial axis in the plane of symmetry of the lens (x-axis, see fig. 6). The variation of the field is dependent only on the proportion S/D and can be found either by calculation or by measurement [6]). In *fig. 7* the variation along the x-axis has been drawn and in *fig. 8* that along the z-axis, both for a series of values of S/D.

It can be seen that the field in the centre of the lens exhibits a saddle point: for the x-direction, the induction at this point is a minimum, for the z-direction, maximum. Consider that the excitation is raised to the level which gives the maximum induction in the gap, a magnitude of 1.8 Wb/m^2 (fig. 7). From fig. 8 it appears that for a given width of gap S the bore D must be made small, or for a given D the width S must be large in order to achieve a strong magnetic field along as great a section of the electron path (z-axis) as possible. A more complete picture is given by *fig. 9*. Here, for each combination of values of S and D, the focal length corresponding to the maximum permissible excitation is plotted (see above). The figure makes it clear that for very different values of D, the same small focall ength can be realised if S is only made large enough. Now the number of ampere turns needed to produce the required induction of 1.8 Wb/m^2 is approximately proportional to the gap width S (the gap presents by far the greatest resistance in the magnetic circuit). To achieve an economical construction, one is therefore forced to make the bore as small as possible.

A limit is set to this by the optical curvature of the field. The electron beam must have a cross-section large enough to "illuminate" a section of the object which is sufficient to fill the fluorescent screen at the smallest magnification with which the microscope is to be used. To avoid an excessive curvature of the field, the cylindrical hole in the

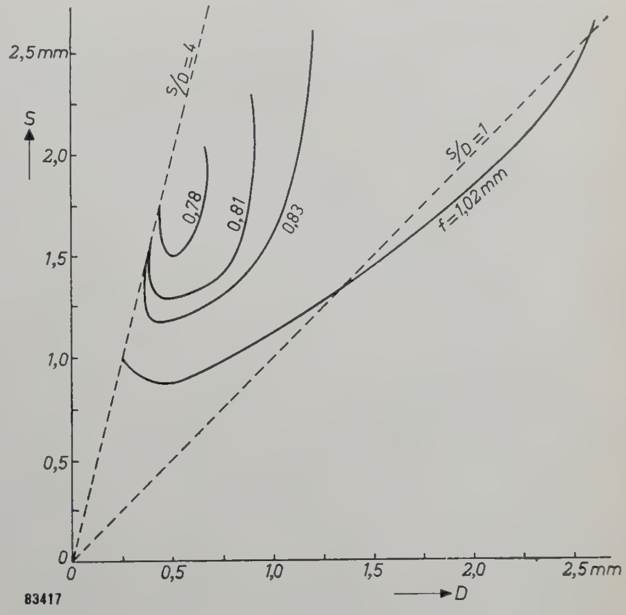

Fig. 9. Focal length f, calculated for lenses of various bore D and gap S when the lens is excited so as to give a maximum induction in the gap of 1·8 Wb/m^2. The acceleration voltage of the electrons is fixed at 75 kV. Points with equal f have been joined in the diagram. (The curves turn upwards slightly at the left-hand side and appear to bend backwards a little at the right; it is not clear whether these effects are real or arise from the approximations in the calculation, but they are of little importance in the S-D range under consideration.

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[6]) For a method of measurement, see e.g. A. C. van Dorsten and A. J. J. Franken, Philips tech. Rev. **15**, 52-55, 1953/54.

pole pieces must be made wide with respect to the necessary cross-section of the beam. On the basis of these considerations [7]), the objective of the EM 75 kV was given a bore of $D = 0.5$ mm.

The gap width S in this lens is 2 mm. These values give the focal length of 0.8 mm already mentioned.

There is not much point in making S greater than 2 mm; this may be seen from fig. 9; the focal length decreases to a limiting value (and even appears to increase again). At $S = 1.3$ mm the minimum value has already been nearly reached. The further ampere-turns needed to make $S = 2$ mm are thus, in fact, not justified merely to obtain the small additional decrease in f, but rather to allow room between the pole pieces to insert the specimen and objective aperture (see below figs 12 and 15).

Let us consider for a moment the decrease in f to a limiting value mentioned above. Fig. 8 does not give any indication of such behaviour: for a fixed D and increasing S/D, high inductions approaching 1.8 Wb/m^2 are obtained over increasingly long sections of the axis, which according to equation (1), should lead to still smaller values of f. But for such "thick" (or rather, long) lenses as we are now considering, we can no longer apply equation (1) which had been simplified to a single term. To understand the behaviour of f for increasingly long lenses, we can best follow the path of an electron which, for example, enters the magnetic field from the left and parallel to the axis. In *fig. 10* we see the paths for three lenses. The electron crosses the axis of the lens at some point. In the case of an *objective* lens one should imagine the object placed at (or, rather, very close to) the point of intersection mentioned above and a scattered electron leaving the object and travelling to the left along the path drawn. The effective focal length is found by the dotted construction. It is seen in the figure that for strong lenses theobject has to be placed some distance within the lens ("immersion lens"), and it can be furtherseen that an extension of the lens has thus very little effect on the focal length of the objective [8]).

In using such thick lenses we must also consider whether our basic assumption is still valid: viz. that the chromatic aberration of the objective is smaller according as the focal length is shorter. Variation of the excitation current I or the acceleration voltage V, which can be combined into an "excitation factor"

$$k = \frac{(\text{Amp. turns})^2}{V},$$

have, for a given lens, an analogous effect to the

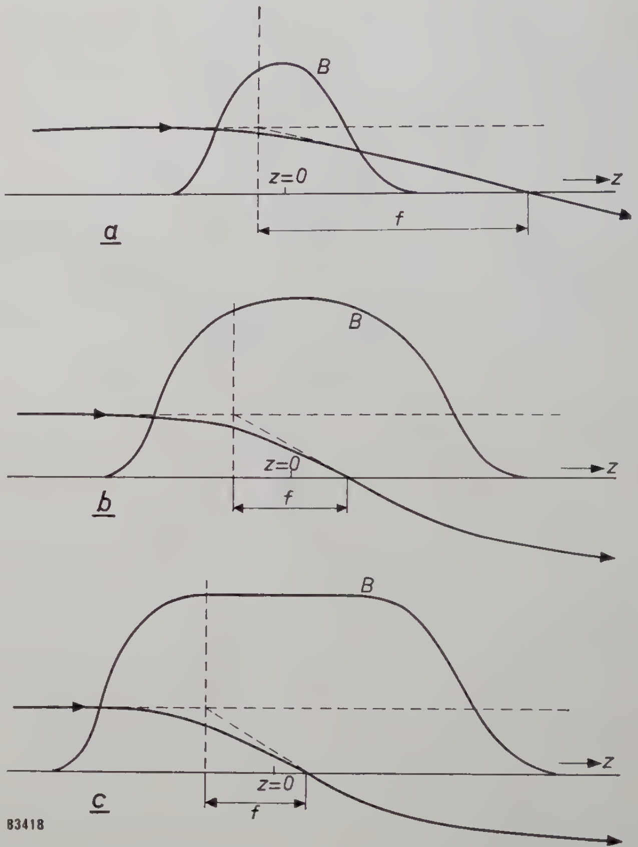

Fig. 10. Path of an electron coming from the left and entering the magnetic field of an electron lens parallel to the axis. The change of induction B is also shown. *a*) Relatively"thin" lens (S/D small). *b*) Longer lens. *c*) Very long lens.
The focal length, i.e. the distance between the focal point and the principal plane is found, for the case of an objective, by drawing the tangent to the electron path at the point where it intersects the axis and finding its intersection with the produced incident path of the electron; this latter intersection defines the position of the principal plane (drawn with a broken line). (For use as a projector, on the other hand, the focal length is found by substituting the linear path of the electron outside the field for the tangent. By producing this linear path backwards one can find the focal point and the principal plane respectively from the intersections with the axis and with the produced incident path.)

The component of the path perpendicular to the plane of the drawing (rotation of the image) has been neglected it is not of importance for the consideration of the focal point.

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[7]) For a fluorescent screen 90×90 mm and the minimum magnification of 1200×, the largest object diameter is a good 100 μ, i.e. about 20% of the bore. In our case, the corners and centre of the object do not lie more than 1.5μ outside the curved object surface. This is about the same Δv as calculated from equation (4) for $\delta_g = 70$Å and $\alpha_0 = 3 \times 10^{-3}$ radians.

[8]) If the object is situated very deep within the objective, the electron rays, before falling on the object (coming from the right in fig. 10), must pass through a large section of the field of the objective, which then behaves (undesirably) as a condenser. This is a further reason for not making S too large. In our case the "condenser action" is not disturbing: the extremely small angle of the (nearly parallel) illuminating electron beam is increased only about 15% and so remains small with respect to α_0 (see equation 4).

variation of the length of the lens which has been discussed above. For a particular lens with various excitation values k, figures are obtained analogous to fig. 10*a* and *b* (except that the *shape* of the field pattern does not change). From this it is plausible that at large values of k, changes in this quantity have relatively less effect on f. This does not mean that chromatic aberrations, which result from fluctuations in k, are correspondingly smaller. In fact, the variation of k now results also in a displacement of the principal plane of the lens: though f may alter less, an extra lack of sharpness occurs because the lens, as it were, is displaced with respect to the fixed object [9]). The resulting chromatic blur (only δ_g, which is the more important) is plotted in *fig. 11* as a function of k for a number of objectives with differing values of S/D.

From fig. 11 it can be deduced that the conclusions drawn from fig. 9 do not have to be revised: for the chosen bore D, a wider gap S (provided the same induction is obtained which means choosing k roughly proportional to S^2) results in smaller aberration, and there is little purpose to be served by making $S > 2$ mm. However, it is of great importance, as shown in fig. 11, that the lens, once constructed with $S/D = 4$, be always excited to the permissible limit, i.e. where $k \approx 170$.

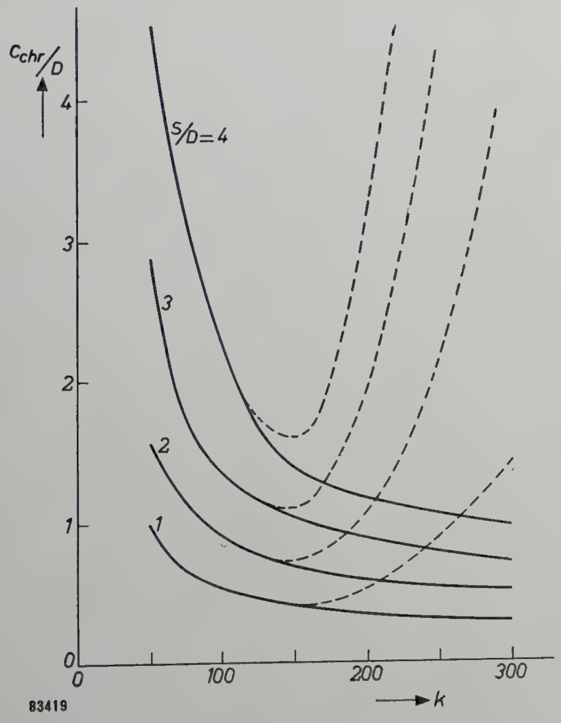

Fig. 11. Chromatic blur for a number of lenses with different S/D, as a function of the excitation factor k. $C_{\rm chr}$ is the proportionality factor between δ_g and $2\alpha_0$, which must be substituted in equation (4) for Δv in more accurate calculations. $C_{\rm chr}/D$ has been plotted to give generally applicable curves. The acceleration voltage is here fixed at 80 kV. These curves may only be used up to that value of k which gives the maximum permissible induction in the gap between the pole pieces.

The full lines apply to the lens when used as an objective ("immersion lens"), the broken lines to use as a projector.

Design of the projector lens

Returning for a moment to fig. 10: in a projector lens, the electrons traverse the whole of the magnetic field. If we follow the path, in fig. 10*b* or c, of an electron coming from the left, we see that the path, after crossing the axis of the lens, is bent back towards the axis again. The electron will thus leave the lens making a smaller angle with the axis than at the point of intersection. This means that the focal length of the lens as projector is longer than as objective. This effect becomes more marked as the lens is made longer or, for a given lens, as the excitation k is increased. Both measures, although they have little further effect on an objective, beyond a certain point will result, for a projector, in an increase in the focal length [10]).

This is accompanied by a larger chromatic aberration; see the broken lines in fig. 11. It appears from this diagram that the abberration is a minimum for a particular excitation factor k_0, which, surprisingly, has about the same magnitude, $k_0 \approx 160$, for projector lenses of all possible forms (various S/D). Moreover, in passing through this "achromatic point" of the curve, the "cushion" distortion which exists with weak excitation of the projector lens is transformed to "barrel" distortion. Thus, at the achromatic point, not only is the influence of fluctuations of the lens current and the acceleration voltage smallest, but the (isotropic) distortion is zero. The projector of the EM 75kV has been designed for use near this point.

Construction of the electron lenses

In *fig. 12* a simplified cross-section of the microscope tube is shown. Of the component parts, which are specified in the caption, we shall first discuss the electron lenses.

The condenser lens is a normal magnetic lens with inserted pole pieces. A diaphragm 0.2 mm in diameter fixes the highest attainable intensity of the electron beam. Variation of the excitation controls the focal length, and with it the angular aperture, of the beam falling on the specimen so as to give the image on the fluorescent screen the required degree of brightness. The lens, together with the electron gun, is mounted in a tube which can be moved bodily in a transverse direction (the adjusting screws for this purpose have not been drawn). In this way the electron gun and condensor lens combination can be accurately centred with the objective lens.

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[9]) Furthermore, the accompanying change of magnification also plays a part. For this see: J. B. Le Poole, Some designs in electron and ion optics, Diss. Delft 1954, p. 47.

[10]) If the field is sufficiently long, (or the excitation strong enough) the electron may cross the axis again, and even a third time, etc.; between these cases the focal length becomes infinite.

The strong excitation of the objective brings the object plane — as in the EM 100 kV 3) — to a point between the pole pieces. It was thus possible to make the objective in two sections and to place the specimen holder (which also includes the objective aperture) between them. The two parts of the lens are screwed together. The sections of the core carry the pole pieces which face each other and are made with great precision from the cobalt-iron alloy already mentioned. The core in the upper half of the lens, contains two auxiliary coils which can be energised with alternating current so as to give an oscillating angle of incidence to the electron beam, facilitating the focusing of the image on the screen; this "wobble focussing device" was explained in the description of the EM 100 kV 3). The lower half of the lens is noteworthy for its core which, with the attached pole piece, can be displaced sideways by screws (not shown in fig. 12). This enables the pole pieces to be centred extremely accurately with respect to one another.

The projector lens is characterised by the separation of the pole pieces which is variable over a wide range. The upper pole piece is mounted outside the vacuum and can be moved about 15 mm in a vertical direction by turning a milled ring which encircles the microscope tube (*fig. 13*). In this way, for constant excitation, the magnification of the lens can be continuously varied from about 10 × to about 90 ×. The magnification of the microscope ranges from about 11 000 × down to 1200 ×, so linking up with magnification obtainable with optical microscopes.

The image remains sharply focused when the magnification is changed, and it does not rotate.

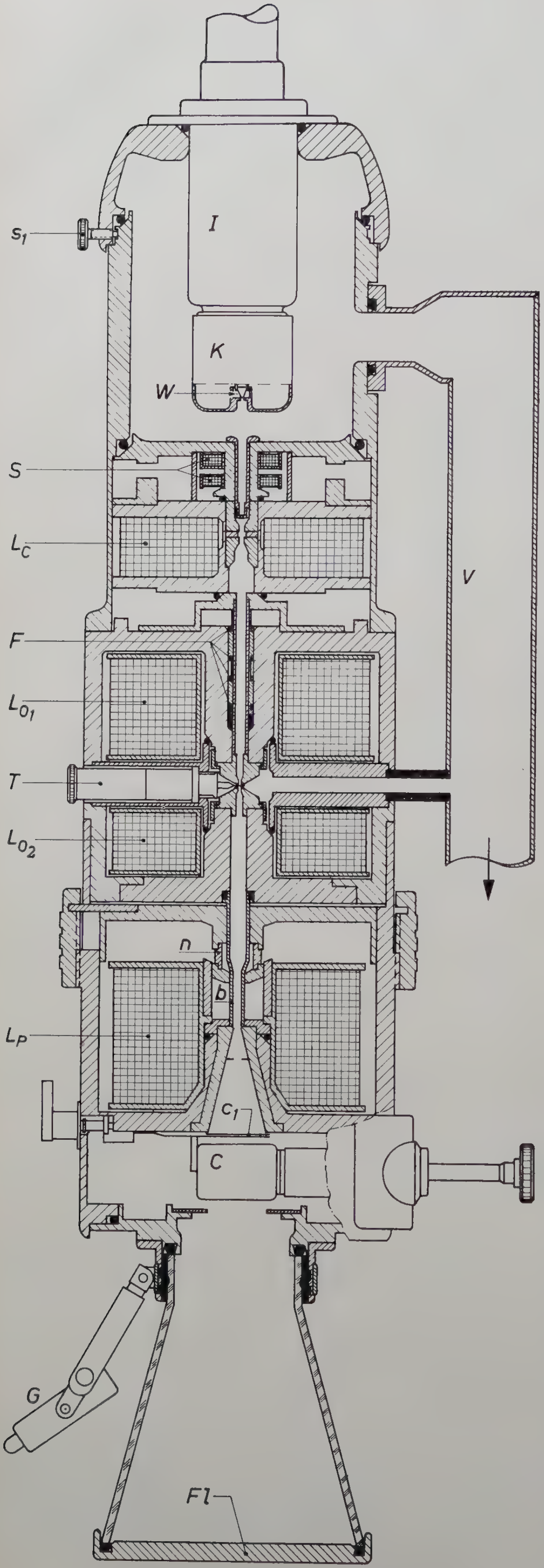

Fig. 12. Cross-section (simplified) of the microscope tube of the EM 75 kV. K cathode with filament *W*; *S* deflection coils for centring the electron beam L_C condenser lens; L_{O_1}, L_{O_2}; objective lens composed of two parts with specimen stage *T*; *F* auxiliary coils to assist in the focusing; L_P projector lens, *n* non-magnetic spacer, *b* brass tube carrying pole-pieces; *C* camera with operating rod (turned through 90° for reasons of clarity), c_1 shutter; *Fl* fluorescent screen; *G* observing lens; *V* vacuum connection. The cap of the tube with the bushing insulator *I*, which varries the cathode, can be moved laterally by means of three screws (s_1 etc.) for centring of a changed filament.

It is not practicable to vary the magnification of an electron microscope by regulating the excitation of the projector or the objective: this has been pointed out on an earlier occasion in this Review (see [1]), p. 40). We may recall here merely that this is a consequence of the desire for an image free of distortion and completely filling the fluorescent screen, even at the smallest magnification. In the case of the EM 75 kV, the excitation of the projector must be kept fixed in order to preserve the minimum sensitivity to fluctuations. The excitation of the objective is rigourously fixed because of the fixed position of the specimen (and thus the object plane). In larger microscopes, such as the EM 100 kV, regulation of the magnification is achieved by the use of intermediate lenses, the excitation of which can be varied over a wide range. For our simple microscope this method was not suitable, since the chromatic blurring caused by fluctuations of k which has been adequately reduced by the design of the objective and projector lenses, would be reintroduced in full via the intermediate lens (at least, for photography). The solution described with the adjustable pole pieces was therefore preferred; it is furthermore, less costly and serves its purpose admirably, due partly to the device described below.

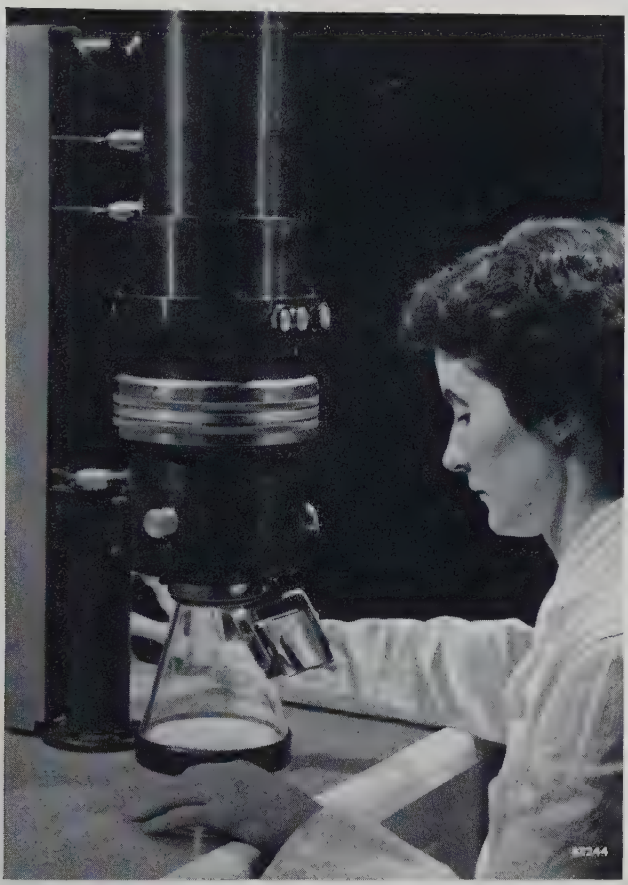

Fig. 13. The microscope tube of the EM 75 kV. By turning the milled ring which encloses the tube, the upper pole piece of the projector lens is displaced. The ring can make $^7/_8$ of a complete turn; this causes the pole piece to move 15 mm in a vertical direction, which alters the magnification by a factor 9. The wall of the vacuum tube is here formed by a thin brass tube (b in fig. 12). which makes a sliding fit in theb ore of the pole pieces, which are thus outside the vacuum.

The sliding pole piece is made with an extra magnetic gap (the sleeve n of non-magnetic material, fig. 12). This forms a sort of additional lens, which, in the highest position of the pole piece, when the strength of the projector and the magnification are at a minimum, reduces the strength of the whole by a further factor of nearly 2. When the pole piece is moved downwards and the lens is thus made stronger, the gap is gradually magnetically short-circuited by the soft iron guide in which the pole piece moves. The weakening additional lens is thus gradually cut out. This device makes it possible to increase the ratio between maximum and minimum projector magnification from about 1 : 5 for the normal construction with one gap, to about 1 : 9.

The variation of the gap (alteration of S at constant D) does not increase the aberrations appreciably. Thus we reap the benefit of choosing the achromatic point for the excitation of the projector, see fig. 11.

Special attention must be paid in this microscope to the centring of the electron lenses. Faulty centring can mean that small fluctuations of the lens currents or of the acceleration voltage cause the image to be displaced laterally (without loss of definition however). For direct observation this is of little importance, but for photography it is fatal. Especially because there is no electronic stabilisation of current and voltage, the instrument makes higher demands on the centring than many more complicated instruments.

The methods of centring — lateral displacement of lenses or pole pieces — have already been mentioned. It may be wondered whether the adjustment is not a difficult and time-consuming business. In fact, a simple and effective routine method has been worked out. The detailed instructions of the method are not within the scope of this article but it may be said that the adjustment is made according to various criteria which can be directly deduced from the electron-optical characteristics of the system. The relative positions of the optical axes of the two lenses is checked by means of the rotation of the image which occurs with changes of the excitation in magnetic lenses. The adjustment of the pole pieces in the objective can be checked further, by reversing the direction of the current in this lens (objective and projector are not connected in series in this microscope): when perfectly centred, the point about which the image rotates with changing excitation is the same for both current directions. The normal direction of the current in the objective and projector lenses is chosen so that the rotation of the image is in opposite directions in the two lenses. Small fluctuations of the current and voltage then result in no appreciable rotation of the image, which could impair the photographic record.

Fig. 14 reproduces a micrograph made with the EM 75 kV, to give an impression of the image quality normally obtainable.

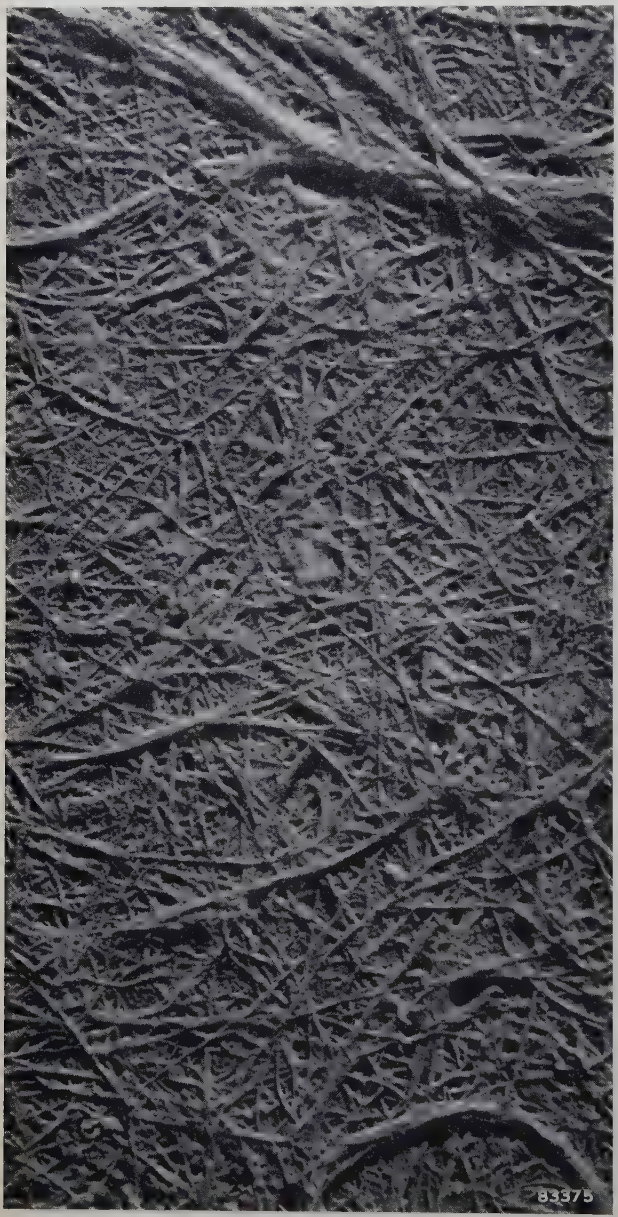

Fig. 14. Animal cellulose (Tunicine). Magnification 20 000 ×. Micrograph made with the EM 75 kV. (L. H. Bretschneider, Utrecht.)

Other components of the microscope body

Only a summary description of the other component parts of the microscope body will be given. The electron gun does not differ in principle from that described for the EM 100 kV [3]). The filament is a V-shaped tungsten wire which is raised to a high potential (maximum 75 kV) with respect to the metal wall of the microscope body. The filament is enclosed by a cathode cap (fig. 12) which is held at a small negative potential with respect to the filament according to the principle of automatic grid bias. This ensures that there is no appreciable variation in the emission current and, at the same time, bunches the emitted electrons. The cathode is mounted as a separate unit in the cap of the tube in such a way that the filament can be easily renewed. The cap, mounted on the microscope body with a rubber vacuum seal, can be displaced laterally a few millimeters with respect to the column by means of three radially placed screws. Thus it is possible, after changing the filament, to centre the electron gun accurately with respect to the condenser. Centring is simplified by four deflection coils, situated between the electron gun and the condenser (fig. 12), which impart small angular deflections to the electron beam.

The specimen stage (*fig. 15*) consists of a metal block which can be moved in two directions perpendicular to the electron beam by means of two adjusting screws, to make it possible to scan the specimen. The specimen, as is customary, is placed on a mesh grid or plate mounted on a rod (as in the EM 100 kV). The specimen stage includes a vacuum seal through which the rod is inserted. A hinged movement of the stage displaces the specimen slightly in an axial direction in the microscope tube. This is necessary in order to keep the specimen in its place under all conditions: the short focal length of the objective reduces the tolerance for the axial position of the object to a few hundredths of a millimeter.

The objective diaphragm has been fitted into a cut-out portion of the specimen stage and, like the specimen, can be displaced in three directions.

The image on the fluorescent screen, of dimensions 90 × 90 mm, is observed in this microscope through the side of the tube (in contrast to the EM 100 kV where the screen is observed through the end of the tube as in a television set); see fig. 13. The conical end of the microscope tube is made of glass for this purpose; lead glass has been chosen, which completely protects the observers (the image can be observed by several persons at the same time) from the X-rays given off by the screen. For focusing, use can be made of a reading lens of magnification about $2^1/_2$ ×.

The image can be recorded on standard 35 mm roll film (as in the EM 100 kV). The internal camera takes a strip of film sufficient for 40 exposures each 28 × 28 mm. The film is brought into the electron beam by pulling out the camera rod with the right hand. At the same time a window in the camera is opened and a shutter, fixed in the microscope tube, is closed. The film is then exposed by operating the shutter with the left hand. With this construction, the need for a shutter mechanism in the sliding camera has been obviated. The shutter is of a type used in some cameras and permits fairly accurately timed short exposures of the order of 1 second. After exposure, the rod is pushed in again, which automatically operates the transport of the film and the counting device. When the film strip is fully exposed, the camera is removed from the microscope and replaced by another loaded camera. This method makes it possible, by placing the loaded camera in a desiccater, to remove so much water vapour before use that evacuation of the microscope tube after changing cameras takes only about 20 minutes.

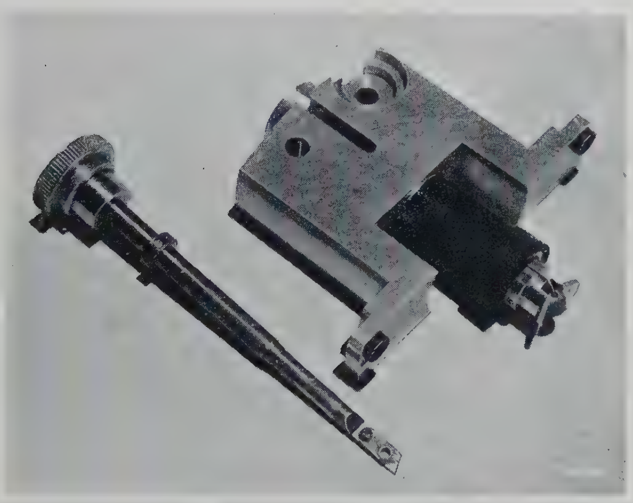

Fig. 15. The specimen stage and specimen holder (left). The cylindrical central section of the specimen stage contains a vacuum lock through which the specimen holder is inserted into the microscope tube.

The vacuum system

With our simplified electron microscope, the need for a vacuum system will probably be felt to be the most important complication over the light microscope. Therefore, the greatest possible simplicity has been aimed at in this equipment, too. The first stage of the vacuum is obtained with a rotary oil pump, the high vacuum by means of an oil diffusion pump with glass wall. The element of the latter is a thick spiral of chrome-nickel wire, which is immersed in the oil to be heated. This method of heating is so efficient that a power of only about 60 watts is required. Since the walls are scarcely heated, no energy is lost and the important advantage is achieved that no water-cooling is required: the natural air-cooling keeps the walls cold enough for the oil vapour to condense. Another great advantage of the small power and accompanying small heat capacity of the heating element is that when evacuating the microscope tube (e.g. after changing film or filament) the vacuum valve may be opened at once: the tube is then pumped to a low vacuum through the oil diffusion pump — a most unusual procedure, which in our case can be applied without any objections since the sudden flow of air cools down the small quantity of oil in a few moments to a temperature where oxidation of the oil need no longer be feared.

The rotary pump has a vibration-free mounting, so that it may be allowed to run while working with the microscope without any deterioration of the sharpness of the micrographs. The high vacuum pump can also be allowed to continue working after the vacuum valve has been closed for the admission of air to the microscope. The operation of the vacuum system is therefore extremely simple.

The safety devices which normally play a large part in vacuum systems, have been reduced here to one automatic valve. This is situated between the rotary backing pump and the oil diffusion pump. The electrically operated valve remains open so long as the mains voltage remains across the motor driving the backing pump. If the motor is stopped or the voltage fails, the valve closes automatically as a result of the atmospheric pressure and, at the same time, the vacuum side of the backing pump is connected with the outside air. Oil from the rotary pump can therefore never be sucked into the vacuum system if the motor stops — an old trouble with many vacuum systems.

The instrument includes the usual precautions against arcing inside the microscope: a relay permits the application of the high voltage to the cathode only when a sufficient vacuum has been reached.

The vacuum is measured by a Philips manometer (Penning gauge).

The mechanical construction of the vacuum system is also worthy of mention. The oil diffusion pump has been suspended inside the desk of the microscope on a specially strengthened section which extends upwards as a vertical vacuum tube with internal diameter of 50 mm. This wide tube ensures a reasonable pumping speed and, thanks to its very firm connection with the desk, performs an important function as stand for the microscope column: at its upper end, the tube carries a connecting block which is fixed with screws to the lower end of the microscope tube. The microscope is rigidly fixed only at this point, so that if vibrations occur, the whole instrument behaves as a rigid body. Such vibrations have therefore no influence on the photographs made and the instrument need not be placed in a vibration-free room or on a special foundation.

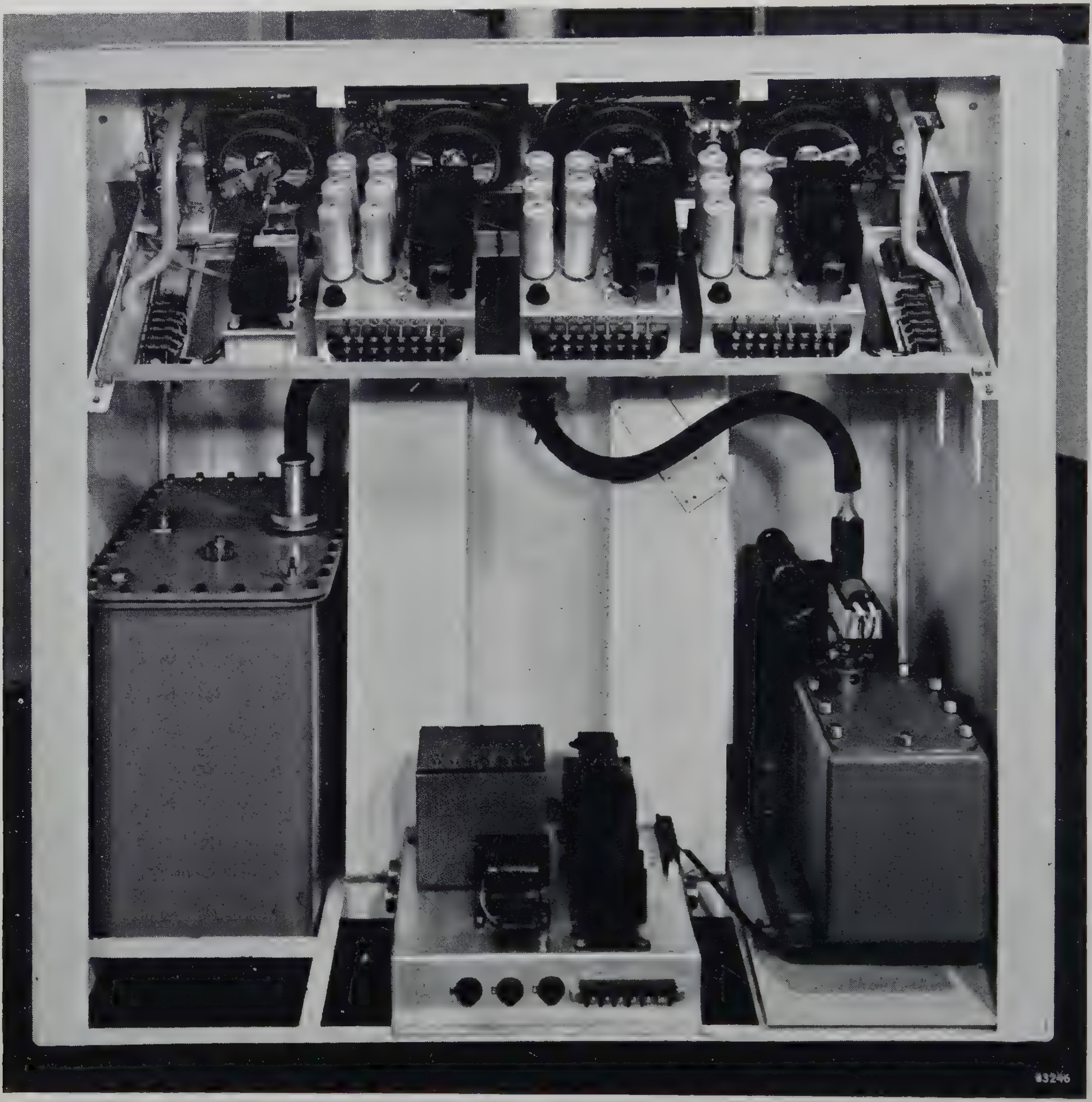

Fig. 16. The desk of the EM 75 kV seen from the back (back panel removed). Bottom left, tank containing the oil-immersed high tension generator, rectifier valves and filament current transformer. Bottom right, backing vacuum pump. Centre magnetic mains voltage stabilizer. Above, rectifiers and smoothing condensers, which supply the energizing current for the three electron lesnses. Behind them is the back of the operating panel with knobs and switches.

In the connecting block is the vacuum valve already mentioned and the tube is connected here by a rubber seal (thus not rigidly connected, to maintain the principle of suspension from one point) to an extension which brings the cathode space and the object space in direct connection with the high vacuum pump (fig. 12). This measure reduces the pumping time from the start to about 15 minutes; when changing the specimen, the vacuum is restored after 20 seconds pumping.

The electrical equipment

The acceleration voltage for the electrons is supplied by a small cascade generator with three rectifier valves. A variable transformer makes it possible to vary the high tension from 0 to 75 kV. The generator, together with the rectifiers, is fitted in an oil bath which can be hermetically sealed. The bath stands on the base of the desk where, in addition to the pumps, the magnetic stabilizer for the mains voltage and the power pack for the lenses, the deflecting coils and the vacuum gauge are housed (*fig. 16*).

The three lenses, condenser, objective and projector, are supplied independently by three power packs, each with their own variable transformer, selenium rectifiers and smoothing condensers. The currents for all the lenses can be continuously varied from zero to the maximum value — we have already seen that one of the uses for this is in the adjustment of the optical axis. The adjusting knobs are all mounted on the front panel of the desk (fig. 1). Here, too, is the switch for reversing the current in the objective lens.

It has been seen that in this electron microscope, no use has been made of electronic stabilization. The instrument does not contain a single amplifier tube, and apart from the rectifiers the microscope tube itself is the only "electron tube" in the apparatus. For an electron microscope with magnetic lenses this may be considered unique.

Summary. The small electron microscope EM 75kV has been constructed to give a resolving power of at least 100 Å. The instrument contains three magnetic lenses: condenser, objective and projector. The objective has a focal length of only 0.8 mm. This makes the "chromatic" aberrations relatively small. The same is true for the projector lens, which is excited in the "achromatic point" of its characteristic. The total result is that for the desired resolving power, fairly large fluctuations of the excitation currents I of the lenses and the acceleration voltage V of the electrons can be permitted, so large, in fact, that electronic stabilization is unnecessary; a simple mains voltage stabilizer of the magnetic type is sufficient, and the microscope contains not a single amplifier tube. Besides this great simplification of the electrical equipment, the vacuum system and mechanical construction have also been simplified without prejudicing the demands of reliable operation, short pumping time and insensitivity to mechanical vibration.

ELECTRONIC EQUIPMENT FOR THE CONTINUOUS MONITORING OF TURBINES

by C. van BASEL, H. J. LINDENHOVIUS and G. W. van SANTEN

621.317.39:621-135

Electronic measuring systems have several features which render their application very attractive outside the field of electrical engineering, for example in mechanical, physical and chemical applications. This article describes one of the latest applications, viz. electronic devices for the continuous control of the behaviour and running conditions of turbines.

Quantities requiring monitoring in turbines

Among the machines that operate under extremely severe physical conditions one should certainly include turbines; they operate at steam pressures of 80 atm or more and at temperatures of 500 °C, which, in combination with very high speeds of rotating parts, set up enormous stresses in the material. At the same time, to ensure high efficiency performance, only very slight tolerances are permissible. Since, moreover, these machines are very expensive, it is obvious that the running conditions of a turbine should be subject to continuous careful attention. Added to this is the fact that even seemingly insignificant defects in a turbine, or slight negligence in its control, may cause serious damage, not only to the machine but also to other things in the vicinity, quite apart from the indirect consequences of the breakdown of the energy supply — whether used to generate electricity or to propel a ship.

In order to illustrate where monitoring is necessary, consider *fig. 1*, which shows a simplified cross-section of the turbine of a turbo-generator. The rotor shaft, rotating at a speed of 3000 r.p.m., is fitted with a number of rows of moving blades. In between the moving blades are rows of guide blades fixed to the casing, which have the task of re-directing the steam on to further rows of moving blades. The rotor shaft is located radially by slide bearings (*1*) and in the axial direction by a thrust bearing (Michell bearing, *2*). The places where the shaft passes through the casing are sealed steam-tight by labyrinth glands (*3*). The two parts of the shaft are connected by a flange coupling (*4*). The turbine rests on a foundation (*6*) to which it is rigidly fixed at a point (*5*) perpendicularly under the thrust bearing. Only at this point (because of the considerable expansion of the turbine) are casing, shaft and foundation mutually fixed.

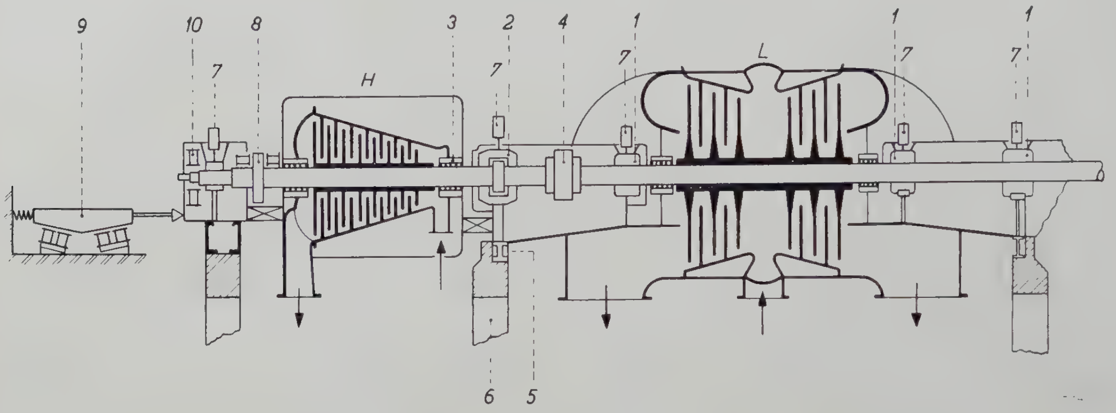

Fig. 1. Cross-section of a steam turbine. *H* high-pressure stage, *L* low-pressure stage (the arrows indicate the direction of the steam). *1* slide bearings. *2* thrust bearing. *3* labyrinth gland. *4* flange coupling. *5* point at which the casing is rigidly connected to the foundation *6*. *7* vibration pick-ups for checking the vibrations of the shaft bearings *1* and *2*. *8* disc for measuring relative changes in length of the shaft. *9* pick-up for measuring the absolute change in length of the casing. *10* disc for measuring the eccentricity.

The first quantity to be considered for measurement is the vibration amplitude in the bearings *1* and *2*. This measurement provides information regarding any unbalance of the rotor system, any play in the bearings or "fouling". A timely indication of any excessive vibration amplitude may prevent enormous damage. To give some impression of the magnitude of the amplitudes concerned it may be mentioned that for a given case in the literature [1]) an amplitude of 10 μ is considered satisfactory, whereas at 45 μ corrective action is urgently called for and at 80 μ it becomes absolutely imperative. (These numbers are applicable to a rotor speed of 3000 r.p.m.).

A second quantity of importance is the change in length of the shaft relative to the casing. For every variation in the steam pressure (which may be caused by a load variation, but is particularly evident during running up and slowing down of the machine) the quantity of heat supplied per second is changing and together with it the temperature of rotor and casing.

Since the rotor possesses a smaller heat capacity and a greater coefficient of thermal conduction than the stationary, thick-walled casing, the former suffers faster changes in temperature and therefore expands more quickly. The small space between moving blades and fixed blades becomes even smaller (especially between the rows farthest removed from the common point of fixture 5) and in the course of a rapid temperature change there is a risk of fouling, with all its serious consequences (such as damage to the labyrinth gland). Continuous monitoring of the relative change in length of the shaft with respect to the casing is therefore most desirable. The maximum permissible deviation is 1-2 mm.

Apart from this relative change in length it is often desired to measure the absolute change in length of the casing. The temperature of the casing in the high-pressure stage is 300-400 °C and the length 2-3 m, so that in heating up from cold the expansion may be 10-20 mm.

The fourth quantity to be measured is the eccentricity of the shaft. Particularly during running up and slowing down of the turbine it is possible that the heating or the cooling along the circumference of the rotor does not take place quite uniformly. The accompanying irregularity of expansion or contraction is manifested in a bending of the shaft. If this effect becomes very pronounced, there is again the risk of serious damage, caused by fouling between moving and stationary blades. For this reason the eccentricity should also be checked, particularly at low rotor speeds.

Among the methods for measuring the above-mentioned quantities, electronic methods are particularly attractive for the following reasons:

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[1]) Measurements by T. C. Rathbone, quoted by I. E. Church, Power 103, July 1950, and K. Federn, Arch. tech. Messen 149, 1954 (No. 222).

1. By means of electronic tubes it is possible to obtain power amplification and consequently a high degree of sensitivity.
2. The virtually inertialess action of electronic amplifiers makes it possible to measure rapidly varying quantities as well.

Added to these are some of the general advantages of electronic measuring methods, viz. the fact that reading or recording may be done at a considerable distance from the object to be measured, and the fact that the properties of electrical circuits are easily adaptable to the circumstances obtaining in the turbine. In the case in question, moreover, it is important that the relative displacement and the eccentricity of the rotating objects can be measured without any mechanical contact with the object and hence without any wear on the detecting element and without the risk that in case of breakdown of the latter, parts of it could interfere with the turbine. We shall now deal more closely with an electronic set-up for the monitoring of turbines.

Monitoring the shaft-bearing vibrations

The amplitude of bearing vibrations is measured with the aid of an electro-dynamic vibration pick-up type PR 9260. As it is a considerable time ago that this instrument was discussed in this Review [2]), we shall once more give a brief description of it. *Fig. 2* shows a longitudinal section of the vibration pick-up. Two parts can be distinguished:

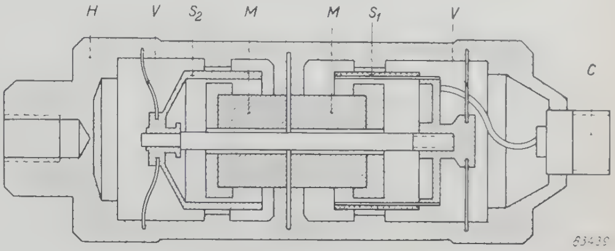

Fig. 2. Cross section of the electro-dynamic vibration pick-up PR 9260. *M* permanent magnet, mounted in the housing *H*. S_1 output coil (with connection contact *C*). S_2 damping coil (copper sleeve acting as a short-circuited winding). The coils are mechanically connected and suspended between the spring membranes *V*.

1. the housing *H* surrounding the rigidly fixed permanent magnet *M*, and
2. the spring membranes *V* connected by a central pin, and carrying the coils S_1 and S_2.

The housing is fixed on the vibrating object — in this case the cap of the bearing in question (*fig. 3*) — and in this way follows every motion of the latter. The spring-mounted pair of coils on the other hand, follows these motions to a far less degree, and hardly at all if the frequency is sufficiently high, in which case it may be considered as stationary which is a characteristic of a pick-up

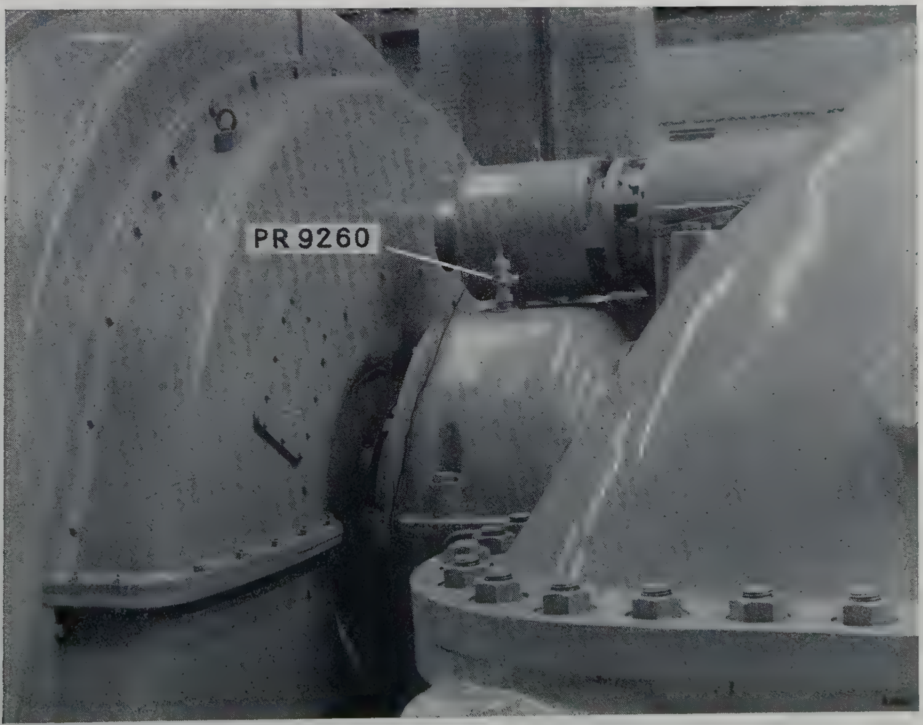

Fig. 3. The vibration pick-up PR 9260 fixed to the bearing cap.

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[2]) J. Severs, Philips tech. Rev. **5**, 230-237, 1940; at the time the type number was GM 5520.

of the seismic type. The magnet connected to the housing moves relative to the more or less stationary coils and induces in the latter a voltage proportional to the velocity of the displacement. Coil S_2 is short-circuited: this provides the "half-critical" damping (i.e. a damping half as great as the critical damping) required for a favourable frequency-response curve. Coil S_1 is connected to an output cable. The ratio of the voltage in this coil to the velocity, is plotted as a function of the frequency in *fig. 4*.

In order to obtain a voltage which is not proportional to the velocity of the displacement, but to the displacement itself, the output voltage of the pick-up has to be integrated over the time. This is easily effected by means of a single *RC*-network.

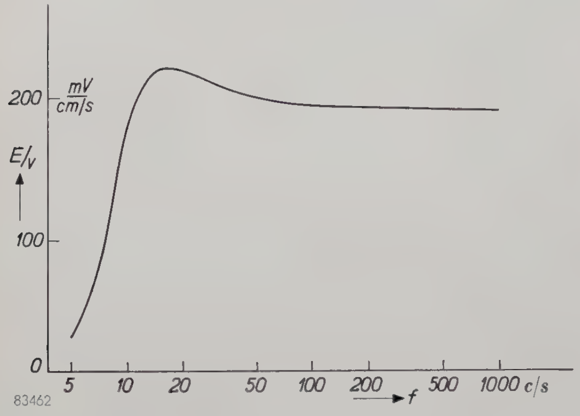

Fig. 4. Response curve of the vibration pick-up PR 9260; the ratio of the output voltage E to the velocity V is plotted as a function of the frequency f.

Fig. 5 shows a block-diagram of the electrical circuit. By means of a rotary switch a maximum of 12 pick-ups can be successively connected to the integrating *RC*-network. This network is followed by an amplifier, a rectifier and a smoothing filter. The direct voltage thus obtained is a measure of the amplitude of the vibrations and may be recorded by means of a recording millivoltmeter (*fig. 6*). In practice it has been found most suitable to select such a sensitivity that a vibration amplitude [3]) of 50 μ corresponds to full deflection of the pointer. The recorder is provided with an adjustable contact which operates an alarm installation as soon as one of the vibration amplitudes exceeds the pre-set value.

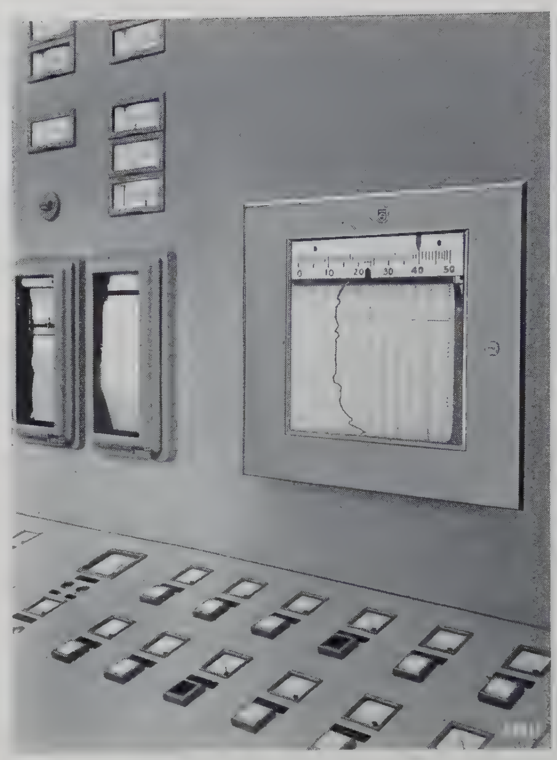

Fig. 6. The recording millivoltmeter type PR 2200 A/21.

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[3]) That is, a peak-to-peak value of 100 μ.

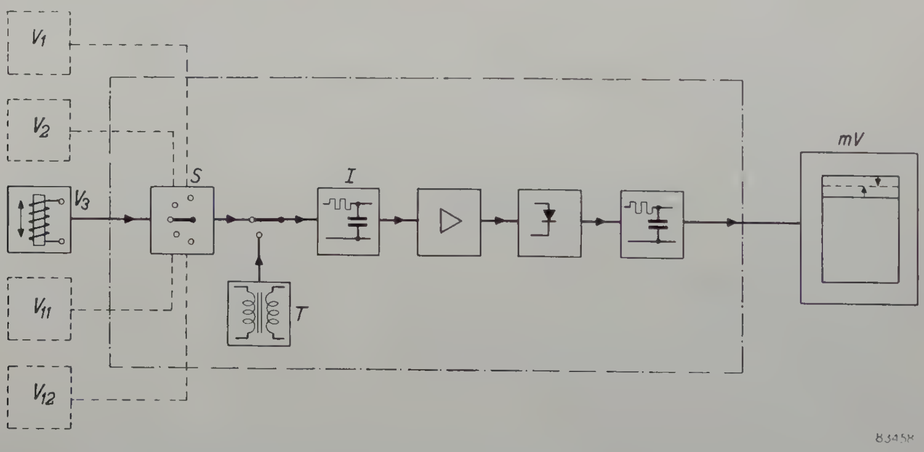

Fig. 5. Block diagram showing the connection of the vibration pick-ups $V_1 ... V_{12}$ (7 in fig. 1) alternately connected via a rotary switch S to the integrating network I. The output voltage of I is applied via an amplifier, a rectifier and a smoothing filter to a recording millivoltmeter mV (see fig. 6). T calibration transformer.

The proper functioning of the equipment may easily be checked at any desired moment by means of an accurately adjustable alternating voltage derived from a transformer (T, fig. 5) connected to the mains.

Monitoring changes in length and eccentricity

Relative change of length of shaft with respect to casing

The relative change in length of the shaft is measured with an inductive displacement pick-up. This instrument (*fig.* 7) consists of an armature (A) of a magnetic material situated between two U-shaped yokes of laminated nicalloy. Each of the yokes is provided with a coil. The two coils, of an equal number of turns, together with two equal resistances form a bridge circuit. One diagonal is fed, via a transformer (T_1), from a valve oscillator (frequency 500 c/s). The primary coil of an output transformer (T_2) is connected to the other diagonal.

When the armature is situated exactly mid-way between the two yokes, the self-inductances of the two coils are equally great and no voltage appears across the primary of transformer T_2. When the yoke is displaced to the right a distance x, the self-inductance of the right-hand coil increases, since here the air gap has become smaller, whereas the self-inductance of the left-hand coil decreases. The bridge circuit is now no longer balanced, and a voltage v is produced across T_2 which is nearly proportional to the displacement x over a wide range (*fig. 8*). If the armature were moved the same distance x to the left, then an equally large voltage would be produced across T_2, this time, however, in opposite phase. In order to distinguish between movement to the right and movement to the left, it is necessary to identify the phase, for which purpose a phase-sensitive detecting circuit is used.

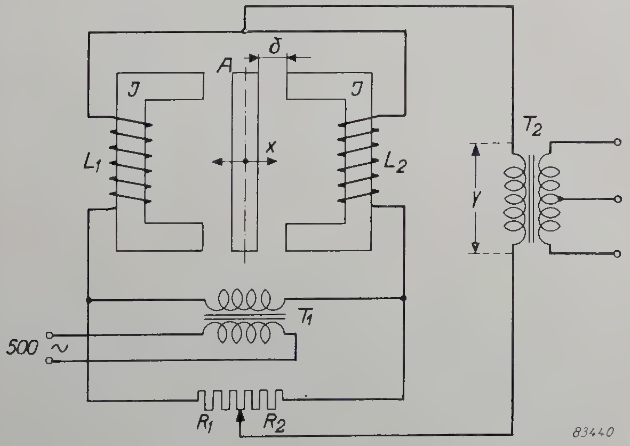

Fig. 7. Schematic diagram of inductive displacement pick-up. The coils L_1 and L_2, together with the resistors R_1 and R_2, form a bridge circuit fed by an valve oscillator (500 c/s) via transformer T_1. The bridge is balanced if armature A is located mid-way between the yokes J. If the armature is located to the left or to the right of the centre, a voltage y is produced across the primary of the output transformer T_2.

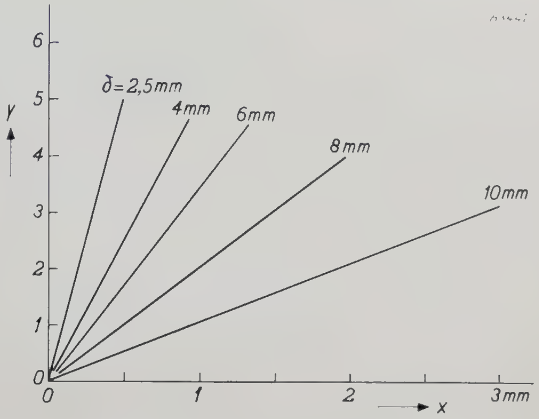

Fig. 8. The voltage y (fig. 7) plotted on an arbitrary scale as a function of the deflection x of the armature from the central position for various values of the air gap δ.

The manner in which a pick-up of this type is used for measuring the change of shaft length of a turbine is shown in *fig. 9*. A disc R (*8* in fig. 1) is fitted on the shaft, which has the same function as the armature A in fig. 7. The two yokes are rigidly connected to the casing.

The working principle needs no further elaboration, but two minor complications may be mentioned here. One is due to the fact that the turbo-gen-

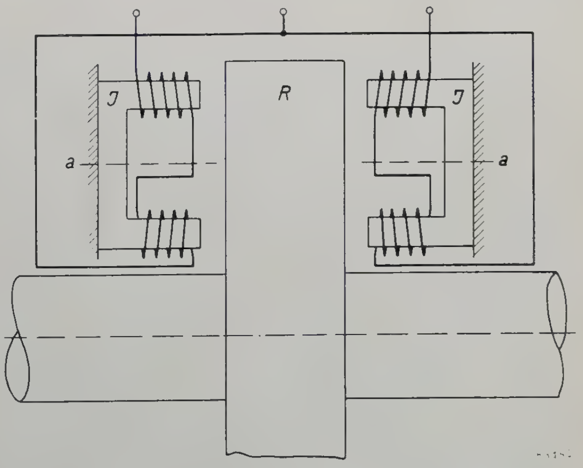

Fig. 9. The displacement pick-up of fig. 7 in a construction suitable for measuring the change in length of the shaft relative to the casing. The yokes J are rigidly connected to the casing. A disc R (of "Permenorm"), fitted on the shaft, functions as armature. (For the sake of clarity the yokes are shown rotated through 90° about line a-a.)

erator is surrounded by a magnetic and an electric field, both of which may impair measurements. The pick-up, therefore, should be carefully screened, magnetically as well as electrically. For this purpose it is housed inside a thick-walled steel box lined with mu-metal. Moreover, the coils are wound in such directions that the influence of an external magnetic field is reduced to a minimum.

The second complication arises from the fact that disc R rotates within the magnetic field of the coils, so that eddy-currents are generated in the disc, giving rise to amplitude and phase errors. To keep these errors as small as possible, the disc is made of a nickel-iron alloy (one of the many types of "Permenorm") with a high resistivity. Use of this material has the added advantage that it is easily machinable.

The air gap on either side of the disc is 10 mm. The maximum displacement that can be measured is 5 mm to either side.

Absolute change in length of the casing

The absolute change in length of the casing is also measured by means of a displacement pick-up (*9* in fig. 1). This is effected by a pick-up of which the armature is connected to the casing and the yokes to the foundation. Since here the displacements to be measured are fairly large (up to 20 mm), very wide air gaps would be required to obtain a linear scale, which would necessitate yokes of very great dimensions. This has been avoided by giving the armature a wedge-like shape (*fig. 10*), such that an axial displacement is converted into a 50 times smaller lateral displacement, the latter being measured in the manner described above. With this (somewhat unusual) reduction of the sensitivity, the air gaps can be confined to 5 mm, so that yokes of normal dimensions can be used. This construction (*fig. 11*) makes it possible to measure displacements up to 50 mm to either side.

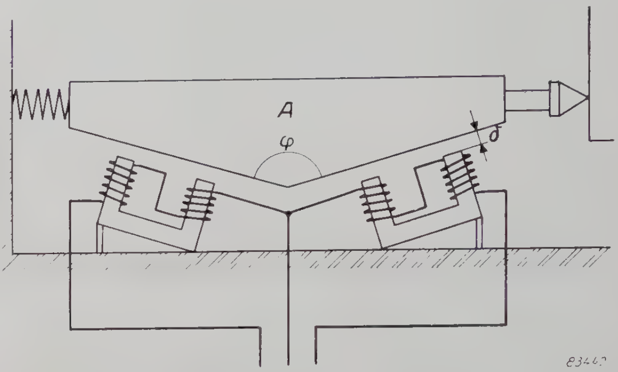

Fig. 10. Displacement pick-up for measuring the absolute change in length of the casing. The principle is the same as that of the pick-up of fig. 7, but owing to the tapered shape of armature A, a change in length of the shaft now corresponds to a 50 times smaller change of the air gap δ. The angle φ, actually about 178°, is shown smaller for the sake of clarity.

Eccentricity

Measuring the eccentricity is again effected by means of an inductive displacement pick-up. Its construction as shown schematically in *fig. 12*. The disc E, shown in this diagram, is located in position *10* in fig. 1 and is made of the same nickel iron alloy as disc R in fig. 9.

Any eccentricity of the shaft is manifested by the fact that the centre of disc E does not remain stationary, but describes a circle of radius e, say. Hence the distance from the circumference of the disc to the yokes changes periodically with an amplitude e.

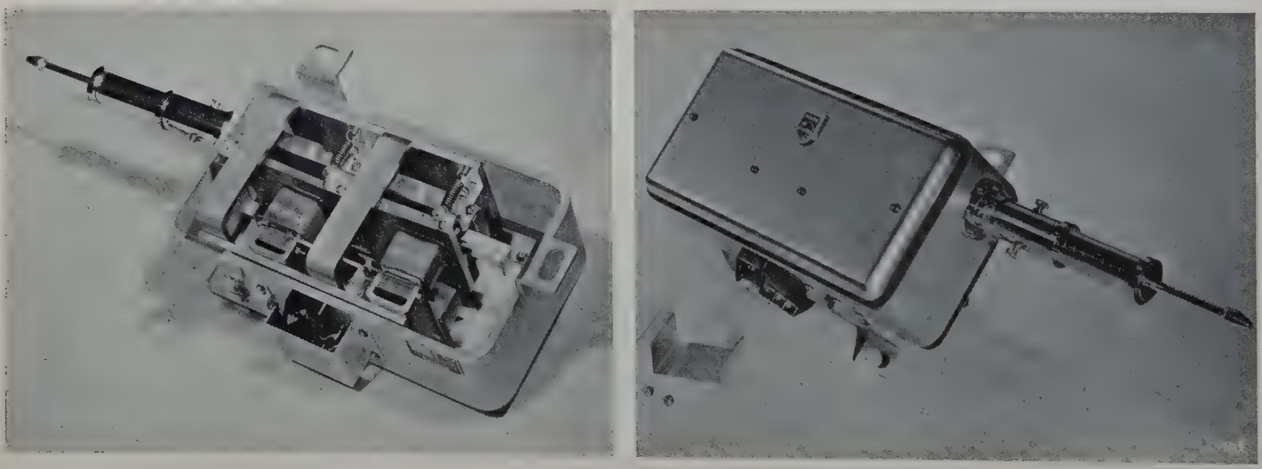

Fig. 11. The displacement pick-up of fig. 10 with the cover removed and closed ready for mounting. For calibration, the amount of the displacement can be read direct from a scale; this reading should correspond to the deflection of the recording meter.

In the two previous cases gradually changing quantities were involved; here, however, we have to deal with a dynamic phenomenon for the distance to be measured changes periodically with a frequency equal to the rotation speed of the shaft. The output voltage of the bridge, therefore, consists of a signal of 500 c/s, modulated with the (far lower) frequency of the shaft. This output voltage is applied via a demodulator to a recording measuring instrument. As long as the rotation speed is very small (below about 1 r.p.s.) — and checking the eccentricity is particularly important at low speeds of rotation, because of the uneven temperature distribution during running up and slowing down — the pointer of the recording meter closely follows the distance variations. As the rotor speed increases, the recorded amplitude decreases, until finally the pointer does not fluctuate at all, but only indicates the average position of the centre of the disc. This information, too, is valuable, since it is an indication regarding the thickness of the oil-film in the bearings.

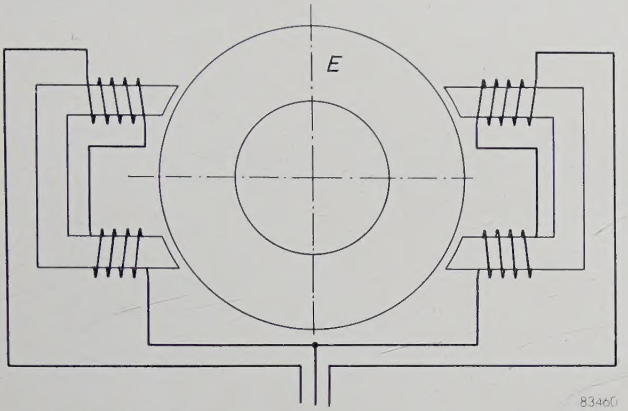

Fig. 12. Inductive displacement pick-up (cf. fig. 7) in a form suitable for measuring the eccentricity of the shaft. Here the armature consists of a disc E (of "Permenorm"), fitted on the shaft.

If it is desired, however, to measure the eccentricity also at high speeds, then, just as when measuring the vibration amplitude, the demodulated output voltage has to be rectified and smoothed, after which the direct voltage thus obtained can be recorded.

The air gap between disc and yokes is adjusted to 2.5 mm; an eccentricity of 0.5 mm produces full scale deflection.

The electrical circuit

Fig. 13 shows a block-diagram of the circuit used for length and eccentricity measurements. A rotary switch driven by a small electric motor makes it possible to connect alternately six inductive pick-ups. The sensitivity and the zero point of each of these pick-ups is adjustable by means of its two potentiometers incorporated in the apparatus.

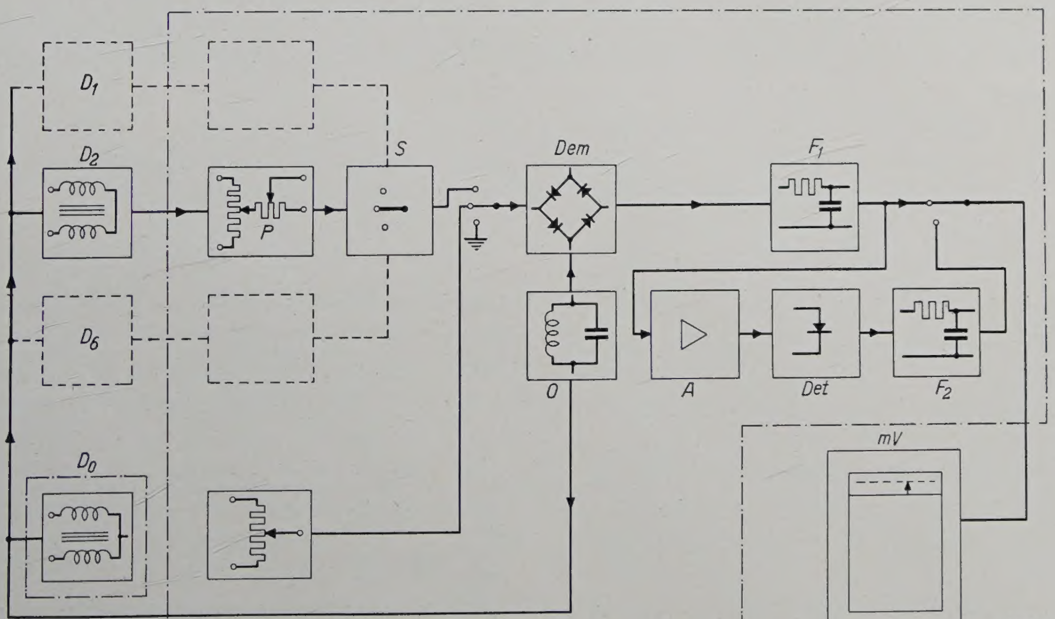

Fig. 13. Simplified block diagram of the circuit for monitoring changes in length and eccentricity. $D_1 \ldots D_6$ six displacement pick-ups. D_0 calibration pick-up. P potentiometers for adjusting the zero point and the sensitivity. S rotary switch. O oscillator 500 c/s. *Dem* demodulator. F_1 smoothing filter 500 c/s. A amplifier. *Det* detector. F_2 smoothing filter shaft frequency. (A, *Det* and F_2 only function for measuring the eccentricity at rotor speeds above 48 r.p.m.) mV recording millivoltmeter.

The demodulation of the output voltage of the bridge takes place in the phase-sensitive detector (*Dem*). The voltage thus obtained is smoothed of the 500 c/s component by a filter (F_1) and the remaining low frequency voltage is applied to a recording instrument. Only for measuring the eccentricity at high rotation speeds is the signal subjected to a subsequent rectification and smoothing as mentioned above. This rectifier (*Det*) may be switched on or off as required; sometimes the switch is operated by a relay, which is automatically energized as soon as the rotor speed exceeds a certain value (e.g. 48 r.p.m., corresponding to 0.8 c/s). The strip of recording chart, shown in *fig. 14,* represents the condition of a turbine passing the critical speed of 48 r.p.m. while slowing down.

The functioning of the equipment can at all times be checked by means of one or more standard pick-ups, of identical construction as the pick-ups mentioned above, but provided with a micrometer screw, by means of which the armature can be displaced over accurately adjustable and known distances.

Those parts of the equipment which are sensitive to fluctuations of the supply voltage are fed from a stabilized voltage supply so that mains-voltage fluctuations cannot impair the results.

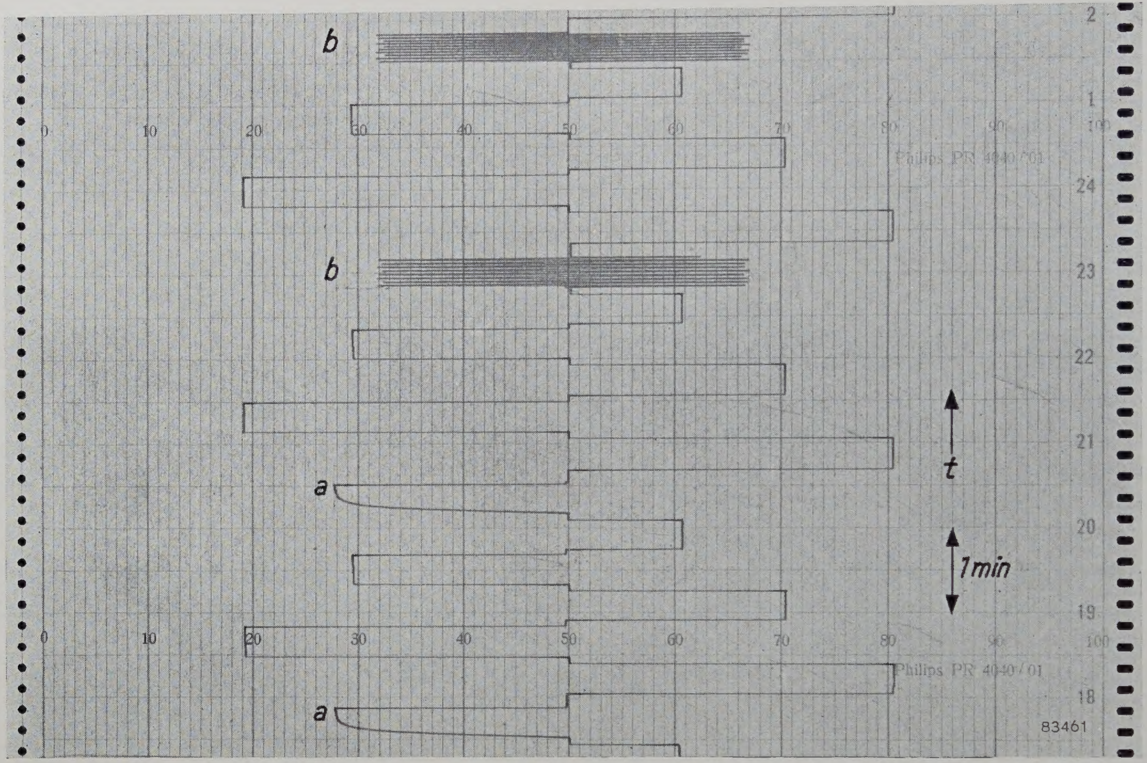

Fig. 14. Section of strip chart, showing the conditions during slowing down of a turbine. At *a* the eccentricity was recorded with the detector *Det* (fig. 13) functioning (rotor speed still above 48 r.p.m.); at *b* without this detector (rotor speed below 48 r.p.m.): the indicator now follows the demodulated alternating voltage. The intermediate rectangular deflections relate to changes in length.

Summary. Turbines are very costly machines, working under severe conditions; moreover, only extremely small tolerances between the rotating and the stationary parts are permissible. The possibility of serious damage can be avoided by keeping a continuous check on certain quantities by means of an installation which gives an alarm if any of them exceeds its critical value.

The quantities to be monitored are the vibration amplitudes of various shaft bearings, changes in length of shaft and casing, and the eccentricity of the shaft. Electronic methods for measuring these quantities have the advantage of high sensitivity, the absence of inertia, and the ability to indicate and record at a distance.

The article describes a seismic electro-dynamic vibration pick-up for checking bearing vibrations, and various types of an inductive displacement pick-up for checking the change in length of the shaft relative to the casing, the absolute change in length of the casing and the eccentricity of the shaft.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk * can be obtained free of charge upon application to Philips Electrical Ltd., Century House, Shaftesbury Avenue, London W.C. 2.

R 234: I. Pelchowitch: A high resolution mass spectrometer with variable-bandwidth measuring circuits (Philips Res. Rep. **9**, 1-41, 1954, No. 1).

A high-resolution spectrometer of the magnetic-sector type is described. Following a general description of the instrument, a detailed analysis and circuitry of the electronic part are given. This is planned so as to include the possibility of varying the time of observation whilst retaining a high sensitivity in the measuring circuits. Accordingly the components units are designed for static and for dynamic operation. The ion-accelerating voltage supply can give a voltage sweep variable in starting-voltage value, amplitude and time dependence. It is also constructed to have a low effective impedance to minimize the disturbing effects of induction and leakage currents. A special DC-coupled wide-band electrometer amplifier is described covering the frequency range 0-1000 c/s. The useful bandwidth can then be selected by the succeeding measuring units in order to have a high signal-to-noise ratio. The circuits of an oscillograph display of the ion currents are given. An added feature of the instrument is an improved space-charge emission regulator used in connection with a modified Nier-type ion source.

R 235: I. Pelchowitch: A study of the evaporation products of alkaline-earth oxides (Philips Res. Rep. **9**, 42-79, 1954, No. 1).

The mass spectrometer described in *R 234* is used to study the evaporation phenomena in systems where the alkaline-earth oxides are coated on electrically heated metal ribbons. BaO evaporates mainly in the form of the oxide when it is coated on Pt and Ni or coated in admixture with SrO and CaO on Pt. When the BaO/Pt system is brought to high temperatures, an ion current of Ba_2O_2 can be measured. In the SrO/Pt and CaO/Pt systems the main evaporation product is the free element accompanied by the oxide and the singly ionized metal ions. The main evaporation product in the BaO/Ta system is free Ba accompanied by the expected amount of the oxide and by singly ionized Ba ions which can be measured at higher temperatures. When the experimental results of ion-current dependence on temperature are fitted to an equation of the form $\log I = -A/T + B$, I being the ion current at a certain M/e value measured at the sample temperature T °K, unexpected results are found. The evaporation-rate curve drawn using $\log_{10} I$ and $10^4/T$ as coordinates is not in all cases a single straight line. The evaporation curve of BaO from all BaO systems coated on Pt can be best described in the measured temperature range as two lines differing in slope joining at the temperature point $T = 1250$ °K. A critical behaviour in the evaporation-rate curve of free Ba evaporating from the system BaO/Ta seems to occur when this temperature point is reached. A different behaviour of the evaporation-rate curve of BaO is observed in the BaO/Ni system, the transition point at 1250 °K disappearing. We are then able to prove, however, that the Ni base metal evaporates through the BaO porous layer and that the evaporation-rate curve of Ni behaves critically in the neighbourhood of $T = 1250$ °K. A transition point in the evaporation-rate curve of free Sr is found in the system SrO/Pt. It is reversible with temperature and the temperature value is $T = 1600$ °K. In view of the unexpected results found in the evaporation-rate curves, resistance measurements of the systems are made using oxide layers pressed between metal electrodes. All the above-mentioned transition points appear clearly in the resistance behaviour with temperature. The difference between Pt and Ni as base metals is also indicated. Finally the experimental results are compared critically with data from the literature.

R 236: P. Zalm, G. Diemer and H. A. Klasens: Electroluminescent Zns phosphors (Philips Res. Rep. **9**, 81-108, 1954, No. 2).

In Part I, an account is given of the preparation of electroluminescent zinc-sulphide powders. The preparation is based on the assumption that a copper-rich layer on the surface of the grains is neccessary for electroluminescence.

In Part II, electrical and optical measurements on electroluminescent ZnS powders are described, including various oscillograms of suspended and binderless settled layers, and stroboscopic observation of the individual crystals by means of a microscope. The maximum efficiency is 1.5 (± 0.2) lm/W; the brightness at 600 V, 3000 c/s is about 1000 lm/m^2. The hypothesis of a barrier action at the surface of the grains is confirmed.

In Part III, the observations of Part I and II lead to the conclusion that electroluminescence is a kind of cathodoluminescence with "slow" electrons. The smallness of the efficiency of electroluminescent phosphors is compared with that of normal phosphors under cathode-ray excitation at low voltage and high current density. A discussion is given of an equivalent circuit for a suspended electroluminescent layer.

R 237: G. Diemer: Electric breakdown and light emission in Cds single crystals (Philips Res. Rep. **9**, 109-121, 1954, No. 2).

With measurements on D.C. breakdown in photoconducting Cds single crystals, activated with Cl, *I-V* characteristics are obtained very similar to those of arc discharges in gases. There is a Townsend region, giving rise to anode light, a region of negative slope where light phenomena occur pointing to a positive streamer discharge, and an arc region of thermal character.

R 238: W. F. Niklas: Die negative Ionenkomponente des Elektronenstrahles in Kathodenstrahlröhren, insbesondere Fernsehbildröhren (Philips Res. Rep. **9**, 122-130, 1954, No. 2).

The electron beam of a cathode-ray tube contains, apart from the electrons, also negative ions which inactivate the fluorescent screen. When in a cathode-ray tube with an electrostatic lens system a transverse magnetic field is superposed on the electrostatic field, it is possible to focus the ions on the screen in sharp points which are arranged according to the mass of the ions. A sharp focus is only obtained if the ions are generated at the same spot as the electrons because the lens system is arranged for sharp focusing of these electrons. An unsharp focus of the ions therefore indicates that the ions must have been generated elsewhere than the electrons. The mass of the ions is obtained by suitable calibration. By means of the degree of sharpness of the focus two ion components can be distinguished: ions generated in the remaining gases contained in the cathode-ray tube (gas ions), and ions from the cathode. By means of a shadow method (a fine gauze placed at different points in the cathode-ray tube) it is shown that the gas ions are generated between the grid and the first anode. By their mass and nature the cathode ions are identified as Cl^{37}, Cl^{35} and CN or C_2H_2, and the gas ions as O, CH, C. Reduction in the residual pressure results in the elimination of the gas ions; the intensity of CN (or C_2H_2) cathode ions reduces with increasing life of the tube.

R 239: H. G. Beljers: Faraday effect in magnetic materials with travelling and standing waves (Philips Res. Rep. **9**, 131-139, 1954, No. 2).

The ferromagnetic Faraday effect in a circular wave guide is described and the approximate theory for the angle of rotation of the plane of polarization is recapitulated. A few experiments are described for Ferroxcube and Ferroxdure samples and the experimental results are compared with the theoretical ones. Finally an experiment with a ferrite specimen in a resonance cavity is reported, demonstrating the positively and negatively rotating components of the mode of oscillation.

R 240: J. S. C. Wessels: Investigations on photosynthesis; the Hill reaction, Part I (Philips Res. Rep. **9**, 140-159, 1954, No. 2).

First part of a treatise on the photochemical reduction of various quinones and dyes by isolated chloroplasts, studied by measuring the redox potential during illumination. Apart from a general introduction, this part contains details of the experimental set-up.